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CENTAUR LIQUID OXYGEN BOOST PUMP VIBRATION TEST

by Hsin Ming Tang
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

The Centaur LOX boost pump was subjected to both the simulated Titan Centaur proof flight and confidence demonstration vibration test levels. For each test level, both sinusoidal and random vibration tests were conducted along each of the three orthogonal axes of the pump and turbine assembly. In addition to these tests, low frequency longitudinal vibration tests for both levels were conducted. All tests were successfully completed without damage to the boost pump.

Summary

A series of vibration tests were successfully conducted on a Centaur LOX boost pump in a non-operating mode. These tests were performed to demonstrate the capability of the pump/turbine to withstand the boost phase of the Titan Centaur Proof Flight (TC-1). The first series of tests were conducted at the simulated TC-1 flight vibration levels. The second series of tests were conducted at higher levels than the first series to demonstrate the existence of a positive structural margin. In the third series, the test scope was extended to demonstrate that low frequency sinusoidal oscillation along the longitudinal axis (POGO) which existed during TC-1 flight could not have caused pump/turbine failure. In both the second and third series of tests, the sinusoidal vibration level was 1.5 times that for the simulated flight level. In the second series, the random vibration level was 2.25 times that for the simulated flight level. Furthermore, a performance check was conducted at the vendor (Sundstrand) test facility before and after each of the simulated TC-1 flight vibration and confidence demonstration test levels. The results from the performance check showed no degradation. After completion of all tests, the boost pump and turbine were disassembled and inspected. There was no evidence of damage to any of the pump or turbine component parts.

Introduction

The Titan Centaur Proof Flight, TC-1, vehicle was launched on February 11, 1974. The mission was not completed because the Centaur main engines failed to start due to insufficient LOX flow to the engines. This failure was caused by failure of the LOX boost pump to provide proper head rise. One possible explanation for the failure was that the boost pump vibration environment during the TC-1 boost phase flight could have damaged the pump/turbine assembly.

The primary objective of the tests, summarized in this report, was to determine if the vibration experienced in the boost phase of TC-1 flight could have caused boost pump failure. These tests consisted of a series of vibration tests of the non-operating LOX boost pump. The first series of tests were conducted at the simulated TC-1 flight vibration levels. The second series of tests were conducted at higher levels to demonstrate a positive structural margin. These test levels are discussed in detail in the section on input vibration test levels. In the third test series, the scope was extended to determine if low frequency longitudinal oscillations (POGO), which existed during the boost phase of the TC-1 flight, could have caused the failure of the LOX boost pump.

Test Specimen and Fixtures

Two sets of specimens were used for this test. The first set consisted of a non-functional (obsolete) pump and turbine, S/N 728/17, and an old LOX tank sump. The second set consisted of a functional rebuilt (flight configuration) pump and turbine, S/N 2431/79, and a good LOX tank sump. For each set, the three units were bolted together and the assembly referred to as the sump/pump/turbine assembly. A cover plate was installed on the upper flange of the sump with provisions for filling the sump with liquid nitrogen and venting the boil-off gas. A photograph of the complete assembly (in the inverted position) is shown in Figure 1. The first set was used for determining the dynamic characteristics of the sump/pump/turbine assembly with a sinusoidal vibration input, and to check the control capability of the testing equipment during random vibration input tests. The results then served as a guide for the later tests. The second set was used to demonstrate that the non-operating pump and turbine assembly could withstand vibration levels equal to, and in excess of, the TC-1 flight vibration levels. Use of the non-functional assembly for checkout precluded possible damage to the functional assembly due to the accumulative effects of fatique to the structural parts.

Two different test fixtures were used for the test. The cylindrical shape fixture, as shown in Figure 2, was used for the longitudinal vibration test along the X-axis, while the trapezoidal shape fixture, as shown in Figure 3, was used for the transverse vibration test along the Y and Z axes. The designation of the coordinate system is identical to the D-1T Centaur vehicle coordinate system.

Test Set Up

The sump/pump/turbine assembly was bolted through the sump upper flange to the top cover plate of either the cylindrical or trapezoidal fixtures, as shown in Figures 4 and 5. For the longitudinal vibration test, as shown in Figure 2, the fixture and base plate were mounted on top of the C-210 2800-pound shaker with the vibration input applied at the bottom of the base plate. For the Y-axis vibration test, as shown in Figure 3, the fixture and base plate were mounted on top of four "team" bearings and the vibration input was applied at the right side of the base plate. For the Z-axis vibration test, in order to avoid moving the heavy fixture, the top cover plate together with the sump/pump/turbine assembly was rotated 90° clockwise.

Instrumentation

A total of 23 accelerometers were used for the test program. All transducers were manufactured by Enderco Company and were capable of recording up to 100 g over a frequency range up to 1000 HZ.

Seventeen (17) accelerometers were mounted on the test specimen, as shown in Figures 6 through 8. Six (6) accelerometers, numbers 1 through 6, were used to select the control accelerometer for the longitudinal (X-axis) and lateral (Y and Z axes) axes tests.

It should be noted that the rotation of the top cover plate (see the previous section) changed the sensitive axis designation for accelerometers number 2, 3, 5, and 6 which were mounted on the base and top plates of the fixture. The location of these 6 accelerometers is shown in Figures 4 and 5. The sensitive axis of each of the 23 accelerometers is defined in Table 1. There is no change of the sensitivities for the accelerometers mounted on the sump/pump/turbine assembly. For the Y-axis test, the accelerometers number 2 and 5 are sensitive in the Y-direction, and the accelerometers number 3 and 6 are sensitive in the Z-direction. However, for the Z-axis test, accelerometers number 2 and 5 are sensitive in the Z-direction, but 3 and 6 are sensitive in the Y-direction.

For testing along each axis, the control accelerometer is defined as the reference accelerometer to which the input vibration was adjusted. After the location of the control accelerometer was determined, eighteen accelerometers were recorded for each test run. These 18 accelerometers consisted of the 17 accelerometers mounted on the test specimen and one control accelerometer, since the other 5 accelerometers mounted on the top and base plates were

used only for selecting the control accelerometer (see the section on control accelerometer location tests).

Input Vibration Test Levels

There were two sets of specimens, non-functional and functional sump/pump/turbine assemblies used for the test. Each test specimen was subjected to a sinusoidal vibration, and a separate random vibration test along three mutually perpendicular axes (X, Y, Z). Because of the different test objectives, the input vibration levels were not the same for each specimen.

(A) Non-Functional Sump/Pump/Turbine Assembly

For each of the three reference axes, the following conditions were used for the sinusoidal vibration only tests:

Frequency Range	Amplitude	Sweep Rate
8 - 500 HZ	0.7G (0-Peak)	1 minute/octave
8 - 500 HZ	1.4G (0-Peak)	1 minute/octave

For the random vibration only tests, TC-1 flight level vibration envelopes, as shown in Figures 9a and 10a, were selected as the input levels for all three axes, with a time duration of three minutes. The derivation of these envelopes is discussed in the following section for the functional assembly.

(B) Functional Sump/Pump/Turbine Assembly

The input vibration test levels for the functional sump/pump/turbine assembly consisted of: (1) TC-1 simulated flight level,

(2) confidence demonstration test level, and (3) low frequency sinusoidal oscillation test level (POGO). The derivation of these three levels are discussed in the following paragraphs.

Data from instrumentation located in the Centaur propulsion equipment region of the TC-1 flight and several Atlas Centaur flights, as shown in Figures 9a and 10a, were used to establish vibration levels for the random vibration only tests. TC-1 flew with two accelerometers in the Centaur propulsion equipment reqion. Measurement CA3ØØ was located on the H_2O_2 bottle support, sensing Y-axis vibration. Measurement CA92Ø was located on the pneumatic panel, sensing vibration normal to the aft bulkhead in a direction approximately 45° from vehicle longitudinal axis (X-axis). Flight data from measurements made on TC-1 during launch and transonic phases are joined by lines on Figures 9a and 10a. Data from the same or similar location on previous Atlas Centaur flights were also plotted on these figures. To be conservative, the envelopes with constant g^2/HZ from 60 HZ to 300 HZ which includes the maxima of both longitudinal and lateral vibration data were selected for the test input level.

The random vibration only confidence demonstration test levels for both longitudinal (X-axis) and lateral (Y and Z axes) directions were 2.25 times TC-1 simulated flight levels, as shown in Figures 9 and 10.

The duration of any significant vibration intensity on TC-1 was about 10 seconds during lift off and 50 seconds during the transonic phase of flight. A duration of three minutes along each axis for both simulated flight level and confidence demonstration tests was therefore conservative.

The sinusoidal amplitude was chosen to be 1.2 G_{rms} (1.7 G_{peak}), which envelopes the maximum G_{rms} values as measured on the aft bulkhead of TC-1. The flight values (G_{rms}) are the magnitudes written in the parenthesis of the legend on Figures 9a and 10a. The confidence demonstration vibration test levels were chosen to be 1.5 times the amplitude of TC-1 flight vibration levels. The conditions for the simulated TC-1 flight and confidence demonstration vibration test levels are as follows:

Test Conditions	Frequency Range (HZ)	Amplitude in. (0-Peak)	Frequency Range (HZ)	Amplitude G (0-Peak)	Sweep Rate
Simulated TC-1 flight	5 - 8	0.25	8 - 500	1.7	1 $\frac{\text{minute}}{\text{octave}}$
Confidence Demonstration	5 - 10	0.25	10 - 500	2.54	1 $\frac{\text{minute}}{\text{octave}}$

The data from the accelerometer mounted on the Viking Dynamic Simulator (VDS) indicated low frequency, high amplitude, longitudinal (X-axis) oscillation during TC-1 flight. It started at approximately 180 seconds after lift-off and continued for approximately 60 seconds. The frequency was approximately 12 HZ. The following two X-axis only tests were conducted to cover this condition.

Even though the response levels on the aft bulkhead were approximately 0.25 G_{peak}, the test levels were conservatively set as below:

Test Conditions	Frequency Range (HZ)	Amplitude G(0-Peak)	Sweep Rate
Simulated TC-1 Flight	8 - 16	1.7	4 $\frac{\text{minutes}}{\text{octave}}$
Confidence Demonstration	10 - 16	2.54	4 $\frac{\text{minutes}}{\text{octave}}$

Control Accelerometer Location Tests

The objective of these tests was to determine the natural frequency of each fixture (without the test specimen) and to select the location of the control accelerometer, i.e., either on the top or the bottom flanges of the fixture. The purpose of this investigation was to prevent the fixture disturbance from distorting the results of a series of sump/pump/turbine assembly vibration tests. The control accelerometer is defined as the reference accelerometer to which the input level was adjusted. There were six accelerometers, three mounted on the top flange and the other three mounted on the bottom flange, used for the vibration survey of each fixture, as shown in Figures 4 and 5.

(A) Control Accelerometer Location for Longitudinal Fixture

For the longitudinal fixture (cylindrical shape) vibration checkout tests, six accelerometers were used, as shown in Figure 4. Table 1 shows the sensing axis of these transducers. For the first

test run, number 1 transducer was used to control the input vibration levels, as shown in Figure 11. Figures 12 through 16 are the vibration responses obtained from the other 5 accelerometers during this run. Figure 14 shows that the natural frequency of the first longitudinal mode was at 480 HZ and the peak response was 25 g. Figures 12, 13, 15, and 16 show that the undesirable and rather high cross talk responses were in the frequency range 380 to 500 HZ. Thus, it was concluded that the number 1 accelerometer should not be used to control longitudinal input vibration levels.

For the second test run, number 4 transducer was used to control the input vibration levels, as shown in Figure 20. Figures 17, 18, 19, 21, and 22 are the vibration responses obtained from the other 5 accelerometers during this test run. Figure 17 shows that the input shaker force decreased as the exciting frequency increased. The input shaker force reached a minimum, when the exciting frequency coincided with the natural frequency of the first longitudinal mode. Figures 18, 19, 21, and 22 show the insignificant cross talk responses. Thus, the number 4 accelerometer was selected to control longitudinal input vibration levels. Furthermore, the control accelerometer located on the top flange was more consistent with the vehicle in flight condition, since the vibration load, during flight, is transmitted from the Centaur aft bulkhead through the sump to the pump and turbine.

(B) Control Accelerometer Location for Transverse Fixture

For the transverse fixture (trapezoidal shape) vibration checkout test, six accelerometers were used, as shown in Figure 5. The sensing axis of the accelerometer numbers 1 through 6 were as shown in Table 1. For the third test checkout run, number 2 transducer was used to control the input vibration levels, as shown in Figure 24. Figures 23, 25, 26, 27, and 28 are the vibration responses obtained from the other 5 accelerometers during this test run. Figure 27 shows that the natural frequency of the first lateral mode was at 250 hertz and the peak response was 46 g. Figures 23, 25, 26, and 28 show that the undesirable and high cross talk responses were in the frequency range 220 to 300 hertz. Thus, it was concluded that the number 2 accelerometer should not be selected to control the transverse input vibration levels.

For the fourth test run, number 5 transducer was used to control the input vibration levels. The input vibration levels for the fourth test run were as shown in Figure 33. Figures 29, 30, 31, 32, and 34 are the vibration responses obtained from the other 5 accelerometers during the fourth test run. Figure 30 shows that the input shaker forces decreased as the exciting frequency increased. The input shaker force reached a minimum when the exciting frequency coincided with the natural frequency of the first lateral mode. Figures 29, 31, 32, and 34 show the insignificant cross talk responses. Thus, the number 5 accelerometer was selected to control

the transverse input vibration levels.

Non-Functional Sump/Pump/Turbine Assembly Test Procedure

The non-functional test specimen was subjected to a sinusoidal vibration only test along each of the three orthogonal axes. For each axis, two different input vibration levels (0.7G and 1.4G as previously described) were used for both dry sump and sump filled with liquid nitrogen tests.

There were two random vibration only test runs along the X and Z axes for the non-functional sump/pump/turbine assembly filled with liquid nitrogen. These two random vibration tests were run at the simulated flight levels. The specification and actual laboratory simulated flight vibration input levels for the random vibration only test, in the directions of both X and Z axes, are shown in Figures 9a, 9b, 10a, and 10b. The maximum variation of the actual test levels (Figures 9b and 10b) were well within the specified tolerance limit of ±3 db. Furthermore, for the X-axis test, the overall G_{rms} of the actual laboratory test levels was 3.1, which was essentially the same as the specification test levels of 3.06 G_{rms}. For the Z-axis vibration test, the overall G_{rms} for the actual laboratory test levels was 1.25 as compared to the specification test level of 1.37. Therefore, the random vibration control capability is acceptable.

After completion of the vibration tests, the non-functional sump/pump/turbine assembly was visually examined for evidence of damage. The decision to continue with the vibration tests on the functional assembly test specimen was based on the acceptability of the visual examination and evaluation of the non-functional test specimen data.

Functional Sump/Pump/Turbine Assembly Test Procedure

The functional sump/pump/turbine assembly was subjected to a series of vibration tests under two different sump and turbine temperature conditions. The sump was filled with liquid nitrogen for both test conditions. For the first series of vibration tests, there was no sump insulation and turbine temperature control. However, for the second series of vibration tests, the sump was insulated and the turbine was heated to better simulate the flight environment. After completion of each series of vibration tests, the assembly was returned to the vendor (Sundstrand) for a performance check. Comparison of the performance before and after the vibration test showed no degradation.

(A) Functional Assembly Test with No Insulation

The functional sump/pump/turbine assembly was first tested at the simulated TC-1 flight levels with no sump insulation and turbine temperature control. For each of the three orthogonal axes, the specimen was subjected to both sinusoidal and random vibration tests separately. Subsequently, the same assembly was subjected to

a low frequency longitudinal (X-axis) sinusoidal only vibration test. The latter low frequency "POGO" test was at the simulated TC-1 flight level with the test frequency range of 8 to 16 HZ and the sweep rate of 4 minutes per octave.

(B) Functional Assembly Test with Insulation

The validity of the first flight level vibration test with no insulation on the sump was questioned because of very low turbine temperature experienced during testing. Turbine temperature during TC-1 flight was approximately +60°F (15.6°C), whereas the turbine temperature during the first flight level vibration tests was estimated to be below -100°F (-73°C). Consequently the sump was insulated, the turbine was heated, and the flight level vibration tests were repeated. Turbine temperature and pump/turbine assembly breakaway torques were measured and recorded before and after each test run.

After the completion of the flight level vibration tests, the confidence demonstration level vibration tests were conducted. The confidence tests were a repeat of the TC-1 flight level sinusoidal only, random only, and "POGO" tests except the vibration levels were increased as previously discussed (see input vibration test levels). These tests were conducted using only the functional assembly, and with the sump insulated and the turbine heated. Turbine temperature and pump/turbine assembly breakaway torques were measured and recorded before and after each test run.

After the completion of the confidence level vibration tests, the pump/turbine assembly was returned to the vendor (Sundstrand) for a performance check. Abbreviated acceptance tests for the pump/turbine assembly were repeated at the vendor test facility. After the performance check, the pump and turbine were completely disassembled and examined for evidence of damage as a result of the vibration test.

Test Results

A summary of the vibration data is presented in tabular form for all sinusoidal vibration tests conducted on both the functional and non-functional test specimens. These data are presented in Tables 2 through 6 for the non-functional test specimen, and in Tables 7 through 11 for the functional test specimen.

Accelerometer response versus frequency plots are also presented in Figures 35 through 106 for the sinusoidal only confidence demonstration level tests on the functional test specimen. The high frequency range (5 to 500 hertz) data are included in Figures 35 through 88, and the low frequency (10 to 16 hertz) dwell test data (POGO) are included in Figures 89 through 106. Due to the voluminous quantity of data plots obtained from the entire test program, no other data plots are included in this report in the interest of brevity. The data plots presented are considered representative of the dynamic characteristics of the pump/turbine assembly, and can be used for future evaluation of flight data and design.

The turbine temperatures and the breakaway torques recorded before and after each of the vibration test runs on the functional test assembly after insulation of the sump and heating the turbine are presented in Table 12.

In summary, all tests were completed satisfactorily. Evaluation of the data from the sinusoidal and random vibrations tests on the non-functional test specimen, and the subsequent inspection, revealed no abnormalities and demonstrated that the control capability of the test equipment was acceptable. The functional test specimen was installed and TC-1 flight level sinusoidal only, random only, and "POGO" vibration tests (without insulation on the sump and without turbine temperature control) were successfully completed.

After insulation of the sump and providing temperature control for the turbine, the TC-1 flight level tests were successfully repeated. Subsequently, confidence demonstration level vibration tests (vibration levels in excess of the TC-1 flight vibration levels) were successfully conducted. The abbreviated acceptance tests conducted on the functional pump/turbine assembly by the vendor (Sundstrand) after the first TC-1 flight level vibration test (without insulation and temperature control), and again after the completion of all vibration tests, showed no degradation in performance from the original acceptance test prior to any vibration. The final disassembly and inspection of the functional pump/turbine revealed no evidence of

damage. The detailed results of the vendor tests, disassembly, and inspection are included in reference 1.

A detailed discussion of the vibration test data and results presented in the tables and figures follows:

(A) Responses at Fundamental Natural Frequency

The fundamental natural frequency of the functional sump/pump/turbine assembly obtained from lateral (both Y and Z axes) vibration tests was in the range of 60 to 68 hertz, as shown in Tables 7 and 9.

The fundamental natural frequency of the non-functional sump/pump/turbine assembly obtained from lateral vibration tests (both Y and Z axes) was in the range of 60 to 70 hertz, as shown in Tables 2 and 4. Thus, the variation in the fundamental natural frequency range was insignificant regardless of the following conditions:

a. dry sump

b. sump filled with liquid nitrogen, no sump insulation, and cold turbine

c. insulated sump filled with liquid nitrogen and heated turbine.

Tables 2, 4, 7, and 9 show that high responses at the fundamental natural frequency of both assemblies occurred at the turbine flange and turbine wheel in the direction of input excitation. Table 2 shows the sinusoidal vibration test results along the Z-axis of the

non-functional sump/pump/turbine assembly for both dry sump and sump filled with liquid nitrogen conditions. This table shows that high responses occurred at the turbine flange and turbine wheel along the Z-axis regardless of the various sump conditions and input vibration levels. At the input vibration level of 1.7 g peak, the responses at the turbine flange and turbine wheel were 37 g peak and 36 g peak, respectively.

Table 9 shows the sinusoidal vibration test results along the Z-axis of the functional sump/pump/turbine assembly for two different sump and turbine conditions. For the first condition, the sump was not insulated and turbine was cold, -100°F (-73°C).

For the second condition, the sump was insulated with 1.5 inches thick foam and the turbine was heated. The temperatures of the turbine are shown in Table 12. Table 9 shows that high responses also existed at the turbine flange and turbine wheel in the direction of the input excitation regardless of the different input vibration levels and various conditions of sump and turbine. At the input vibration level of 1.7 g peak and the first condition of sump and turbine, the responses at the turbine flange and turbine wheel were 27 g peak and 31 g peak, respectively. At the input vibration level of 1.7 g peak and the second condition of the sump and turbine, the responses at the turbine flange and turbine wheel were 28 g peak and 31 g peak, respectively.

Table 4 shows the sinusoidal vibration test results along the Y-axis of the non-functional sump/pump/turbine assembly for both dry sump and sump filled with liquid nitrogen conditions. This table shows that high responses occurred at the turbine flange and turbine wheel along the Y-axis regardless of the different sump conditions and input vibration levels. At the input vibration level of 1.7 g peak, the responses at the turbine flange and turbine wheel were 42 g peak and 40 g peak, respectively.

Table 7 shows the sinusoidal vibration test results along the Y-axis of the functional sump/pump/turbine assembly for the two different sump and turbine conditions.

Table 7 shows that high responses also existed at the turbine flange and turbine wheel in the direction of the input excitation regardless of the different input vibration levels and various conditions of sump and turbine. At the input vibration level of 1.7 g peak and the first condition of sump and turbine, the responses at the turbine flange and turbine wheel were 38 g peak and 44 g peak, respectively. At the input vibration level of 1.7 g peak and the second condition of the sump and turbine, the responses at the turbine flange and turbine wheel were 34 g peak and 42 g peak, respectively.

The longitudinal (X-axis) fundamental natural frequency of both functional and non-functional sump/pump/turbine assemblies is not

well defined, since several modes were closely coupled. The peak responses and corresponding frequencies are presented in Tables 6 and 11.

Table 6 shows the sinusoidal vibration test results along the X-axis of the non-functional sump/pump/turbine assembly for both dry sump and sump filled with liquid nitrogen conditions. For the dry sump condition, high responses existed at the turbine flange along the direction of input excitation and at the pump shaft along the Z-axis. At the input vibration level of 1.4 g peak, the response at the turbine flange was 12 g peak along the X-axis, while the responses at the pump shaft was 12.5 g peak along the Z-axis. For the sump filled with liquid nitrogen, high responses existed at the turbine flange and pump shaft along the direction of input excitation. At the input vibration level of 1.4 g peak, the responses at the turbine flange and pump shaft were 20 g peak and 10 g peak, respectively. Similarly, for an input of 1.7 g peak, the responses were 16 g peak and 18 g peak, respectively.

Table 11 shows the sinusoidal vibration test results along the X-axis of the functional sump/pump/turbine assembly for two different sump and turbine conditions. For the first condition, the sump was not insulated and turbine was cold, -100°F (-73°C). Secondly, the sump was insulated with 1.5 inches thick foam and the turbine was heated.

The temperatures of the turbine are shown in Table 12. For the first condition, high responses exist at the turbine flange and the quill shaft along the X-axis, and at the turbine wheel along the Y-axis. At the input vibration level of 1.7 g peak, responses at the turbine flange and quill shaft were 6 g peak and 6.2 g peak, respectively, and response at the turbine wheel was 6 g peak. For the second condition, high responses exist at the turbine flange along the X-axis, and at the turbine wheel along the Y-axis. At the input vibration level of 1.7 g peak, the responses at the turbine flange and turbine wheel were 16 g peak and 35 g peak, respectively.

(B) <u>Responses at Second Natural Frequency</u>

The range of the second natural frequency of the non-functional sump/pump/turbine assembly obtained from lateral (both Y and Z axes) vibration tests varied according to the following two sump conditions and is shown in Tables 3 and 5. For the dry sump, the second natural frequency was in the range of 180 to 190 HZ. For the sump filled with liquid nitrogen, the second natural frequency was in the range of 130 to 150 HZ.

The second natural frequency of the functional sump/pump/turbine assembly (with and without insulation) as obtained from the lateral vibration tests (both Y and Z axes) was in the range of 130 to 150 HZ and is shown in Tables 8 and 10. Thus, the range of the second natural frequency of both assemblies, for both Y and Z axes, is dependent on whether the sump is full or empty.

Tables 3, 5, 8, and 10 show that the high response at the second natural frequency of both assemblies occurred at the pump shaft in the direction of input excitation. Table 3 shows results of the sinusoidal vibration test along the Z-axis for the non-functional sump/pump/turbine assembly with two various sump conditions. For the dry sump, it could not be definitely determined that the high response was at the pump shaft along the Z-axis because of bad data. However, for the sump filled with liquid nitrogen, the test data shows that the high response was at the pump shaft along the Z-axis. At the input vibration level of 1.7 g peak, the response at the pump shaft was 19 g peak.

Table 5 shows the sinusoidal vibration test results along the Y-axis of the non-functional sump/pump/turbine assembly with two various sump conditions. For the dry sump, the high response was at the pump shaft along the Y-axis. At the input vibration level of 1.4 g peak, the high response at the pump shaft was 68 g peak. For the sump filled with liquid nitrogen, the high response was at the pump shaft along the Y-axis. At the input vibration level of 1.4 g peak (1.7 g peak), the response at the pump shaft was 31 g peak (32 g peak).

Table 8 shows the sinusoidal vibration test results along the Y-axis of the functional sump/pump/turbine assembly under two different conditions. For the first condition, the sump was not insulated and

the turbine was cold, -100°F (-73°C). Secondly, the sump was insulated with 1.5 inches thick foam and the turbine was heated. Turbine temperatures are shown in Table 12. Table 8 shows that the high response was at the pump shaft in the direction of the input excitation regardless of the different input vibration levels and conditions of the sump and turbine. At the input vibration level of 1.7 g peak and the first condition of the sump and turbine, the response at the pump shaft along the Y-axis was 12.5 g peak. At the input vibration level of 1.7 g peak and the second condition of the sump and turbine, the response at the pump shaft along the Y-axis was 14 g peak.

Table 10 shows the sinusoidal vibration test results along the Z-axis of the functional sump/pump/turbine assembly with two different sump and turbine conditions. For the first condition, the sump was not insulated and the turbine was cold, -100°F (-73°C). Secondly, the sump was insulated with 1.5 inches thick foam and the turbine was heated. Turbine temperatures are shown in Table 12. Table 10 shows that the high response was at the pump shaft in the direction of input excitation regardless of the different input vibration levels and conditions of the sump and turbine. At the input vibration of 1.7 g peak and the first condition of the sump and turbine, the response at the pump shaft along the Z-axis was 19 g peak. At the input vibration level of

1.7 g peak and the second condition of the sump and turbine, the response at the pump shaft along the Z-axis was 24 g peak.

(C) Magnification Factor (Q) and Damping Coefficient (ζ)

Two important dynamic characteristics, magnification factor (Q) and damping coefficient (ζ), are included in Tables 7 through 10. When a structure is subjected to a forced vibration, Q is defined as the response at a specific location divided by the input. At resonance, the damping coefficient can be obtained from the formula, $Q = 1/2\zeta$. Tables 7 through 10 show the sinusoidal vibration test results along three orthogonal axes of the functional sump/pump/turbine assembly. Tables 7 and 9 show the test results at the fundamental mode along Y and Z axes, respectively. The data presented in these tables show that the high responses were at the turbine flange and turbine wheel in the direction of input excitation. The damping coefficient at these two locations was in the range of 2 to 3 percent. Tables 8 and 10 show the test results at the second mode along Y and Z axes, respectively. The data presented in these two tables show that the high response was at the pump shaft in the direction of input excitation. The damping coefficient at this location was in the range of 4 to 7 percent.

Conclusion

The Centaur LOX boost pump and turbine assembly successfully passed both the simulated TC-1 (Titan Centaur proof flight) flight and the

confidence demonstration (in non-operating mode) vibration test levels. Each of the test levels consisted of both random and sinusoidal vibration along each of the three orthogonal axes of the assembly. A functional performance check of the assembly was conducted at the vendor (Sundstrand) test facility before and after each vibration test level. Comparison of the performance before and after each vibration test level showed no degradation. After completion of all tests the pump and turbine were completely disassembled and all parts were inspected. No evidence of damage was found in any of the component parts. Thus, these tests demonstrated that the assembly could sustain the vibration experience in the boost phase of both the TC-1 flight and future Atlas/Centaur and Titan/Centaur flights. Furthermore, the test results demonstrated that low frequency longitudinal oscillations (POGO) could not damage the turbopump assembly.

REFERENCES

1. Sundstrand Corporation Engineering Test Report No. ATR 5008-43, "NASA Vibration Test Unit, TC-1 Investigation," Dated February 10, 1975, prepared by L. E. Gebacy.

TABLE I - Accelerometer Locations

Acc. No.	Location	Accelerometer Sensitivity		
		X-Axis Test	Y-Axis Test	Z-Axis Test
1	Base Plate (270° Azim)	X	X	X
2	Base Plate (270° Azim)	Y	Y	Z
3	Base Plate (270° Azim)	Z	Z	Y
4	Top Flange (270° Azim)	X	X	X
5	Top Flange (270° Azim)	Y	Y	Z
6	Top Flange (270° Azim)	Z	Z	Y
16	Sump/pump Flange (270° Azim)	X	X	X
17	Sump/pump Flange (270° Azim)	Y	Y	Y
18	Sump/pump Flange (270° Azim)	Z	Z	Z
19	Sump/pump Flange (90° Azim)	X	X	X
22	Turbine Flange (270° Azim)	X	X	X
23	Turbine Flange (270° Azim)	Y	Y	Y
24	Turbine Flange (270° Azim)	Z	Z	Z
25	Turbine Flange (90° Azim)	X	X	X
28	Turbine Wheel (270° Azim)	X	X	X
29	Turbine Wheel (270° Azim)	Y	Y	Y
30	Turbine Wheel (270° Azim)	Z	Z	Z
31	Quill Shaft (270° Azim)	X	X	X
32	Quill Shaft (270° Azim)	Y	Y	Y
33	Quill Shaft (270° Azim)	Z	Z	Z
34	Pump Shaft (270° Azim)	X	X	X
35	Pump Shaft (270° Azim)	Y	Y	Y
36	Pump Shaft (270° Azim)	Z	Z	Z

Note: All Accelerometers Are Manufacture By Endevco And Have A Capability up to 100 g's Over A Frequency Range Up to 500 Hz

TABLE 2 Sinusoidal-only Test

Non-Functional Sump/pump/Turbine Assembly

Z-Axis Test Results

First Resonance Range – 60 – 68 HZ

			Dry sump				Sump Fill with LN_2			
Acc. NO.	Location	Direct.	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak
5	Top Flange (Control Acc)	Z	10-100	0.7	10-100	1.4	10-100	1.4	10-100	1.7
16	Pump/sump Flange(L)	X	62	1.8	60	3.2	64	1.7	66	2.3
17	Pump/sump Flange(L)	Y	62	2.5	62	3.6	64	2.4	66	2.3
18	Pump/sump Flange(L)	Z	62	2.3	60	5.2	62	4.7	68	5.8
19	Pump/sump Flange(R)	X	62	1.9	60	3.6	62	1.7	64	1.8
22	Turbine Flange (L)	X	62	5.4	62	10.5	62	10.5	65	12
23	Turbine Flange (L)	Y	62	5.4	62	9.6	62	11	64	14
24	Turbine Flange (L)	Z	64	18.5	60	22.0	62	33	64	37
25	Turbine Flange(R)	X	62	5.8	62	8.6	62	11	62	12
28	Turbine Wheel	X	62	2.8	62	6.0	62	3.0	62	4.4
29	Turbine Wheel	Y	62	3.0	60	10.5	65	7.8	68	11.5
30	Turbine Wheel	Z	62	18.0	60	33.0	62	28	64	36
31	Quill Shaft	X	64	1.7	64	4.6	Bad Data		66	6.6
32	Quill Shaft	Y	62	2.0	62	14.0	Bad Data		60	13
33	Quill Shaft	Z	60	7.0	62	5.2	Bad Data		64	5.6
34	Pump Shaft	X	62	2.1	62	4.0	62	1.8	62	1.15
35	Pump Shaft	Y	62	2.3	62	8.2	62	2.1	68	2.6
36	Pump Shaft	Z	Bad Data				60	8.5	64	9.5

TABLE 3 Sinusoidal-Only Test

Non-Functional Sump/Pump/Turbine Assembly

Z-Axis Test Results

Second Resonance Range < Dry Sump (180-190 HZ) / Sump With LN_2 (130-140 HZ)

			Dry Sump				Sump Fill With LN_2			
Acc. No.	Location	Direct.	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak
5	Top Flange (Control)	Z	100-200	0.7	100-200	1.4	100-200	1.4	100-200	1.7
16	Pump/sump Flange (L)	X	180	2.3	180	9.2	140	3.3	140	2.4
17	Pump/sump Flange (L)	Y	180	3.0	190	6.2	140	1.8	140	1.2
18	Pump/sump Flange (L)	Z	180	3.6	180	9.0	140	2.8	140	3.0
19	Pump/sump Flange (R)	X	180	3.0	180	9.6	140	3.2	140	2.8
22	Turbine Flange (L)	X	190	2.3	190	7.2	140	5.8	140	5.2
23	Turbine Flange (L)	Y	190	2.5	190	6.8	135	4.6	140	3.9
24	Turbine Flange (L)	Z	190	2.7	190	7.8	140	5.0	140	4.2
25	Turbine Flange (R)	X	180	2.2	180	5.4	140	4.2	130	3.3
28	Turbine Wheel	X	190	1.8	190	7.6	135	1.3	130	1.3
29	Turbine Wheel	Y	190	1.4	180	9.0	135	3.4	140	3.2
30	Turbine Wheel	Z	190	3.7	180	8.4	140	3.5	130	3.0
31	Quill Shaft	X	190	4.8	190	9.5	Bad Data		140	7.4
32	Quill Shaft	Y	180	6.8	190	15.0	Bad Data		130	11.0
33	Quill Shaft	Z	180	6.8	190	10.5	Bad Data		140	7.5
34	Pump Shaft	X	190	2.6	180	6.2	130	6.2	130	3.1
35	Pump Shaft	Y	190	12.5	180	28.0	130	16	140	15
36	Pump Shaft	Z	Bad Data				130	21	140	19

TABLE 4 Sinusoidal - Only Test

Non-Functional Sump/Pump/Turbine Assembly

Y - Axis Test Results

First Resonance Range - 60-70 HZ

Acc. NO	Location	Direct.	Dry Sump				Sump Fill With LN_2			
			f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak
5	Top Flange (control)	Y	10-100	0.7	10-100	1.4	10-100	1.4	10-100	1.7
16	Pump/sump Flange (L)	X	64	2.45	64	5.2	68	4.8	65	5.2
17	Pump/sump Flange (L)	Y	64	2.55	62	5.7	62	3.6	65	3.8
18	Pump/sump Flange (L)	Z	68	1.15	66	3.1	65	2.4	65	1.9
19	Pump/sump Flange (R)	X	64	2.65	64	5.2	65	5.0	65	5.4
22	Turbine Flange (L)	X	64	12	62	23	66	23	66	25
23	Turbine Flange (L)	Y	62	20	60	35	66	29	65	42
24	Turbine Flange (L)	Z	64	3.9	65	7.0	66	16	62	15
25	Turbine Flange (R)	X	64	5.6	65	9.5	66	10.5	66	11
28	Turbine Wheel	X	66	5.0	62	10	68	7.2	65	7.4
29	Turbine Wheel	Y	60	21.5	62	42	64	27	65	40
30	Turbine Wheel	Z	64	3.2	62	7.3	65	11.4	66	16
31	Quill Shaft	X	64	1.8	62	6.5	62	4.2	70	12
32	Quill Shaft	Y	62	4.4	60	7.7	62	8.2	66	10
33	Quill Shaft	Z	62	5.6	62	13	62	1.5	70	13
34	Pump Shaft	X	62	1.9	60	4.2	66	12	62	1.4
35	Pump Shaft	Y	62	4.6	62	9.2	66	9.0	66	10.5
36	Pump Shaft	Z	Bad Data				60	3.6	66	3.3

TABLE 5 Sinusoidal-Only Test

Non-Functional Sump/Pump/Turbine Assembly

Y-Axis Test Results

Second Resonance Range < Dry Sump (170-190 HZ) / Sump With LN_2 (130-150 HZ)

			Dry Sump				Sump Fill With LN_2			
Acc. NO	Location	Direct.	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak
5	Top Flange (control)	Y	100-200	0.7	100-200	1.4	100-200	1.4	100-200	1.7
16	Pump/Sump Flange (L)	X	180	5.2	180	12	140	5.6	140	6.8
17	Pump/Sump Flange (L)	Y	180	5.2	180	13	140	4.6	140	5.6
18	Pump/Sump Flange (L)	Z	190	2.5	190	6.0	140	1.8	140	2.2
19	Pump/Sump Flange (R)	X	180	5.2	190	14.5	140	6.6	140	7.8
22	Turbine Flange (L)	X	180	4.2	180	21	140	4.8	140	7.4
23	Turbine Flange (L)	Y	180	3.4	180	7.2	140	6.2	140	8.6
24	Turbine Flange (L)	Z	180	2.7	190	6.4	140	4.7	140	5.6
25	Turbine Flange (R)	X	190	3.9	190	9.3	140	3.5	140	5.0
28	Turbine Wheel	X	180	1.9	180	5.0	140	1.9	140	3.4
29	Turbine Wheel	Y	180	3.2	180	13	130	6.0	130	6.8
30	Turbine Wheel	Z	190	1.2	190	4.1	140	3.0	150	3.4
31	Quill Shaft	X	180	4.6	180	10.5	Bad Data		150	19
32	Quill Shaft	Y	180	6.0	180	12	Bad Data		140	20
33	Quill Shaft	Z	180	9.4	180	16	130	3.7	150	16
34	Pump Shaft	X	180	3.8	170	8.2	140	21	130	13
35	Pump Shaft	Y	180	25	180	68	130	31	130	32
36	Pump Shaft	Z	Bad Data				130	16	140	14

TABLE 6 Sinusoidal-Only Test

Non-Functional Sump/pump/Turbine Assembly

X-Axis Test Results

Resonance Range: Dry Sump (160-220HZ); Sump Fill With LN_2 (140-190HZ)

			Dry Sump				Sump Fill With LN_2			
Acc.No	Location	Direct.	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak
4	Top Flange (control)	X	100-250	0.7	100-250	1.4	100-250	1.4	100-250	1.7
16	Pump/sump Flange (L)	X	220	2.9	220	5.0	140	7.0	190	7.0
17	Pump/sump Flange (L)	Y	220	1.6	220	4.5	170	2.5	190	4.7
18	Pump/sump Flange (L)	Z	220	1.5	220	3.4	170	1.6	190	3.2
19	Pump/sump Flange (R)	X	220	4.2	200	5.2	140	4.8	180	8.2
22	Turbine Flange (L)	X	220	9.4	220	12	180	10	170	12
23	Turbine Flange (L)	Y	220	2.9	190	8.5	150	9.0	180	9.6
24	Turbine Flange (L)	Z	190	4.8	180	5.4	170	10	190	9.0
25	Turbine Flange (R)	X	170	5.4	160	12	130	20	190	16
28	Turbine Wheel	X	220	7.2	220	11	150	6.6	190	8.6
29	Turbine Wheel	Y	220	5.4	220	12	160	6.0	190	9.5
30	Turbine Wheel	Z	200	3.2	220	9.0	170	5.6	190	7.4
31	Quill shaft	X	230	5.6	180	7.0	140	8.0	180	12.5
32	Quill shaft	Y	180	2.2	210	6.2	180	4.6	180	13.5
33	Quill Shaft	Z	220	2.2	180	4.0	160	5.0	180	13
34	Pump shaft	X	220	5.6	220	6.8	140	10	180	18
35	Pump shaft	Y	200	5.8	180	11	140	6.4	190	11.5
36	Pump shaft	Z	200	5.0	190	12.5	140	5.2	170	5.6

TABLE 7 Sinusoidal-Only Test

Functional Sump/Pump/Turbine Assembly

Y-Axis Test Results

First Resonance Range 60-68HZ

Sump Filled With Liquid Nitrogen

			No Insulation				1.5" Thick Foam Insulation							
Acc. No.	Location	Direct.	f(HZ)	Gpeak	Q	ζ	f(HZ)	Gpeak	Q	ζ	f(HZ)	Gpeak	Q	ζ
5	Top Flange(control)	Y	10-100	1.7	1	—	10-100	1.7	1	—	10-100	2.54	1	—
16	Sump/Pump Flange(L)	X	68	4.4	2.6	0.19	62	3.3	1.9	0.36	64	5.2	2.0	0.25
17	Sump/pump Flange(L)	Y	64	3.0	1.8	0.28	Bad Data				64	6.2	2.4	0.20
18	Sump/pump Flange(L)	Z	64	1.9	1.1	0.45	62	1.4	0.8	0.67	62	5.0	2.0	0.25
19	Sump/Pump Flange(R)	X	68	4.2	2.5	0.20	68	3.6	2.1	0.24	64	5.6	2.2	0.22
22	Turbine Flange (L)	X	62	21	12.3	0.04	64	19	11.2	0.04	64	27	10.6	0.04
23	Turbine Flange(L)	Y	64	38	22.4	0.02	64	34	20	0.03	62	46	18.1	0.03
24	Turbine Flange(L)	Z	66	6.5	3.8	0.13	62	9.4	5.5	0.09	62	12	4.7	0.11
25	Turbine Flange(R)	X	Bad Data				64	9.0	5.3	0.09	62	11.5	4.5	0.11
28	Turbine Wheel	X	68	7.1	4.2	0.12	66	9.0	5.3	0.09	68	12.5	4.9	0.10
29	Turbine Wheel	Y	62	44	25.9	0.02	64	42	24.8	0.02	64	62	24.4	0.02
30	Turbine Wheel	Z	66	6.6	3.9	0.13	64	17	10	0.05	68	20	7.9	0.06
31	Quill Shaft	X	66	12	7.1	0.07	62	7.0	4.1	0.12	60	16	6.3	0.08
32	Quill Shaft	Y	68	11	6.5	0.08	62	10	5.9	0.08	68	14	5.5	0.09
33	Quill Shaft	Z	66	16	9.4	0.05	62	13	7.6	0.08	62	17	6.7	0.07
34	Pump Shaft	X	66	2.8	1.6	0.31	62	3.5	2.1	0.24	62	2.9	1.1	0.45
35	Pump Shaft	Y	64	6.6	3.9	0.13	62	6.6	3.9	0.13	64	11.5	4.5	0.11
36	Pump Shaft	Z	64	3.2	1.9	0.26	62	4.0	2.4	0.21	62	5.4	2.1	0.23

TABLE 8 Sinusoidal-Only Test

Functional Sump/Pump/Turbine Assembly

Y-Axis Test Results

Second Resonance Range 130-160 HZ

Sump Filled With Liquid Nitrogen

			NO Insulation				1.5" Thick Foam Insulation							
Acc. NO.	Location	Direct.	f(HZ)	Gpeak	Q	ζ	f(HZ)	Gpeak	Q	ζ	f(HZ)	Gpeak	Q	ζ
5	Top Flange (control)	Y	100-200	1.7	1	—	100-200	1.7	1	—	100-200	2.54	1	—
16	Sump/Pump Flange (L)	X	150	2.2	1.3	0.38	130	2.2	1.3	0.39	150	4.0	1.6	0.31
17	Sump/Pump Flange (L)	Y	150	1.5	0.9	0.56	Bad Data				140	6.0	2.4	0.21
18	Sump/Pump Flange (L)	Z	150	0.85	0.5	1.00	130	0.8	0.5	1.00	150	1.7	0.7	0.71
19	Sump/Pump Flange (R)	X	150	2.7	1.6	0.31	150	2.2	1.3	0.38	150	4.6	1.8	0.28
22	Turbine Flange (L)	X	150	2.9	1.7	0.29	150	2.7	1.6	0.31	150	6.4	2.5	0.20
23	Turbine Flange (L)	Y	150	2.3	1.4	0.36	150	2.0	1.2	0.42	150	4.4	1.7	0.29
24	Turbine Flange (L)	Z	150	1.7	1.0	0.50	140	1.4	0.8	0.63	140	2.8	1.1	0.45
25	Turbine Flange (R)	X	Bad Data				140	2.2	1.3	0.38	140	4.9	1.9	0.26
28	Turbine Wheel	X	150	1.15	0.7	0.71	150	1.6	0.9	0.56	160	6.0	2.4	0.21
29	Turbine Wheel	Y	150	3.0	1.8	0.28	150	3.5	2.1	0.24	150	8.4	3.3	0.15
30	Turbine Wheel	Z	150	2.1	1.2	0.42	150	1.6	0.9	0.56	150	4.4	1.7	0.29
31	Quill Shaft	X	150	8.0	4.7	0.11	150	3.5	2.1	0.24	140	13	5.1	0.09
32	Quill Shaft	Y	150	8.0	4.7	0.11	140	6.8	4.0	0.13	140	15	5.9	0.08
33	Quill Shaft	Z	160	8.0	4.7	0.11	140	4.2	2.5	0.20	140	15	5.9	0.08
34	Pump Shaft	X	150	2.6	1.5	0.33	140	2.8	1.6	0.31	140	6.8	2.7	0.19
35	Pump Shaft	Y	150	12.5	7.4	0.07	140	14	8.2	0.06	140	29	11.4	0.04
36	Pump Shaft	Z	150	5.6	3.3	0.15	140	9.8	5.8	0.08	140	21	8.3	0.06

TABLE 9 Sinusoidal-Only Test

Functional Sump/Pump/Turbine Assembly

Z-Axis Test Results

First Resonance Range 60-68HZ

Sump Filled With Liquid Nitrogen

			NO Insulation				1.5" Thick Foam Insulation							
Acc. NO.	Location	Direct.	f(HZ)	Gpeak	Q	ζ	f(HZ)	Gpeak	Q	ζ	f(HZ)	Gpeak	Q	ζ
5	Top Flange (control)	Z	10-100	1.7	1	—	10-100	1.7	1	—	10-100	2.54	1	—
16	Sump/pump Flange (L)	X	68	1.05	0.6	0.83	64	1.2	0.7	0.71	62	2.2	0.9	0.56
17	Sump/pump Flange (L)	Y	62	1.1	0.7	0.71	Bad Data				60	4.5	1.8	0.28
18	Sump/pump Flange (L)	Z	62	3.8	2.1	0.24	62	3.1	1.8	0.28	60	5.0	2.0	0.25
19	Sump/pump Flange (R)	X	68	1.0	0.6	0.83	62	1.6	0.9	0.56	60	2.3	0.9	0.56
22	Turbine Flange (L)	X	64	5.0	2.9	0.17	62	7.6	4.5	0.11	60	15.5	6.1	0.08
23	Turbine Flange (L)	Y	62	9.6	5.6	0.09	62	11	6.5	0.08	60	22	8.7	0.06
24	Turbine Flange (L)	Z	60	27	15.9	0.03	62	28	16.5	0.03	60	47	18.5	0.03
25	Turbine Flange (R)	X	62	2.9	1.7	0.29	62	11	6.5	0.08	60	21	8.3	0.06
28	Turbine Wheel	X	Bad Data				62	4.6	2.7	0.19	62	6.0	2.4	0.21
29	Turbine Wheel	Y	62	7.6	4.5	0.11	62	9.6	5.6	0.09	62	19	7.5	0.07
30	Turbine Wheel	Z	64	31	18.2	0.03	62	31	18.2	0.03	60	50.0	19.7	0.03
31	Quill Shaft	X	65	8.0	4.7	0.11	68	6.6	3.9	0.13	60	9.0	3.5	0.14
32	Quill Shaft	Y	60	13	7.6	0.07	66	7.6	4.5	0.11	60	10	4.5	0.11
33	Quill Shaft	Z	62	9.2	5.4	0.09	64	13	7.6	0.07	60	19	8.3	0.06
34	Pump Shaft	X	65	1.8	1.1	0.45	62	2.1	1.2	0.42	60	3.6	1.2	0.42
35	Pump Shaft	Y	65	1.9	1.2	0.42	68	2.2	1.3	0.38	60	3.5	1.4	0.36
36	Pump Shaft	Z	64	6.0	3.5	0.14	66	5.8	3.4	0.15	60	8.8	3.5	0.14

TABLE 10 Sinusoidal-Only Test

Functional Sump/Pump/Turbine Assembly

Z-Axis Test Results

Second Resonance Range 130-150 HZ
Sump Filled With Liquid Nitrogen

			NO Insulation				1.5" Thick Foam Insulation							
Acc. NO.	Location	Direct	f(HZ)	Gpeak	Q	ξ	f(HZ)	Gpeak	Q	ξ	f(HZ)	Gpeak	Q	ξ
5	Top Flange (Control)	Z	100-200	1.7	1	—	100-200	1.7	1	—	100-200	2.54	1	—
16	Sump/Pump Flange(L)	X	150	1.3	0.8	0.63	140	1.8	1.1	0.45	140	3.0	1.2	0.42
17	Sump/Pump Flange(L)	Y	140	1.1	0.6	0.83	Bad Data				140	4.4	1.7	0.29
18	Sump/Pump Flange(L)	Z	140	2.4	1.4	0.35	140	3.5	2.1	0.24	140	4.2	1.7	0.29
19	Sump/Pump Flange(R)	X	150	1.5	0.9	0.56	140	2.4	1.4	0.35	150	3.3	1.3	0.38
22	Turbine Flange (L)	X	150	2.4	1.4	0.35	140	2.5	1.5	0.33	140	4.6	2.7	0.19
23	Turbine Flange (L)	Y	150	1.8	1.1	0.45	140	2.5	1.5	0.33	150	5.0	2.0	0.25
24	Turbine Flange (L)	Z	140	2.1	1.2	0.42	140	2.8	1.6	0.31	140	4.2	1.7	0.29
25	Turbine Flange (R)	X	140	2.0	1.2	0.42	140	3.3	1.9	0.26	130	7.2	2.8	0.18
28	Turbine Wheel	X	Bad Data.				140	2.6	1.5	0.33	140	3.0	1.2	0.42
29	Turbine Wheel	Y	150	2.1	1.2	0.42	150	3.9	2.3	0.22	150	7.6	3.0	0.17
30	Turbine Wheel	Z	150	3.0	1.8	0.28	140	3.3	1.9	0.26	140	6.0	2.4	0.21
31	Quill Shaft	X	140	12	7.1	0.07	140	9.8	5.8	0.08	140	14	5.5	0.09
32	Quill Shaft	Y	150	14	8.2	0.06	140	12	7.1	0.07	130	14	5.5	0.09
33	Quill Shaft	Z	150	11	6.5	0.08	140	11.5	6.8	0.07	130	19	7.5	0.07
34	Pump Shaft	X	140	3.2	1.9	0.26	140	3.2	1.9	0.26	140	6.8	2.7	0.19
35	Pump Shaft	Y	140	9.0	5.3	0.09	140	16	9.4	0.05	140	22	8.7	0.06
36	Pump Shaft	Z	140	19	11.1	0.05	140	24	14.1	0.04	140	35	13.8	0.04

TABLE II Sinusoidal-Only Test

Functional Sump/Pump/Turbine Assembly

X-Axis Test Results

Resonance Range – 140-200 Hz

			No Insulation		1.5" Thick Insulation			
Acc. No.	Location	Direct.	f(HZ)	Gpeak	f(HZ)	Gpeak	f(HZ)	Gpeak
4	Top Flange (control)	X	100-200	1.7	100-200	1.7	100-200	2.54
16	Sump/Pump Flange (L)	X	200	3.4	180	6.6	170	7.6
17	Sump/Pump Flange (L)	Y	200	2.3	180	9.6	180	9.0
18	Sump/Pump Flange (L)	Z	200	1.2	170	3.3	180	4.2
19	Sump/Pump Flange (R)	X	200	3.7	170	7.2	180	9.2
22	Turbine Flange (L)	X	200	4.6	170	16	170	16
23	Turbine Flange (L)	Y	180	2.3	170	12	180	15
24	Turbine Flange (L)	Z	200	2.4	170	6.0	170	9.6
25	Turbine Flange (R)	X	200	6.0	170	13	170	14
28	Turbine Wheel	X	190	4.6	170	17	190	19
29	Turbine Wheel	Y	200	6.0	180	35	180	24
30	Turbine Wheel	Z	180	3.0	170	19	170	28
31	Quill Shaft	X	190	6.2	170	8.6	150	10.5
32	Quill Shaft	Y	200	4.4	170	12	150	9.2
33	Quill Shaft	Z	190	6.0	160	12.5	140	15
34	Pump Shaft	X	190	5.8	170	12.5	160	16
35	Pump Shaft	Y	180	3.0	170	7.6	150	16
36	Pump Shaft	Z	180	2.4	170	5.2	150	11

TABLE 12

Temperature And Torque Data Before And After Each Test

Input Level	Test Axis	Ambient Temperature		Torque		Remarks
		Before Test	After Test	Before Test N-M (In.-Oz)	After Test N-M (In.-Oz)	
1.7 Gpeak (sine)	Y	25°C (77°F)	25°C (77°F)	0.169 (24)	0.169 (24)	Tables 7 and 8 (1.5" Thick Insulation)
2.54 Gpeak (sine)	Y	22.2°C (72°F)	22.2°C (72°F)	0.169 (24)	0.169 (24)	Tables 7 and 8 (1.5" Thick Insulation)
1.7 Gpeak (sine)	Z	17.2°C (63°F)	15.6°C (60°F)	0.169 (24)	0.169 (24)	Tables 9 and 10 (1.5" Thick Insulation)
2.54 Gpeak (sine)	Z	15.6°C (60°F)	14.4°C (58°F)	0.169 (24)	0.169 (24)	Tables 9 and 10 (1.5" Thick Insulation)
1.7 Gpeak (sine)	X	8.3°C (47°F)	2.8°C (37°F)	0.169 (24)	0.226 (32)	Table 11 (1.5" Thick Insulation)
2.54 Gpeak (sine)	X	22.2°C (72°F)	22.2°C (72°F)	0.169 (24)	0.169 (24)	Table 11 (1.5" Thick Insulation)
1.98 Grms (Random)	Y	21.1°C (70°F)	21.1°C (70°F)	0.169 (24)	0.169 (24)	
1.98 Grms (Random)	Z	19.4°C (67°F)	17.2°C (63°F)	0.169 (24)	0.169 (24)	1.5" Thick Insulation
4.6 Grms (Random)	X	22.2°C (72°F)	22.2°C (72°F)	0.169 (24)	0.169 (24)	
1.7 Gpeak (POGO)	X	2.8°C (37°F)	0.6°C (33°F)	0.226 (32)	0.226 (32)	
2.54 Gpeak (POGO)	X	22.2°C (72°F)	22.2°C (72°F)	0.169 (24)	0.169 (24)	

E-8427

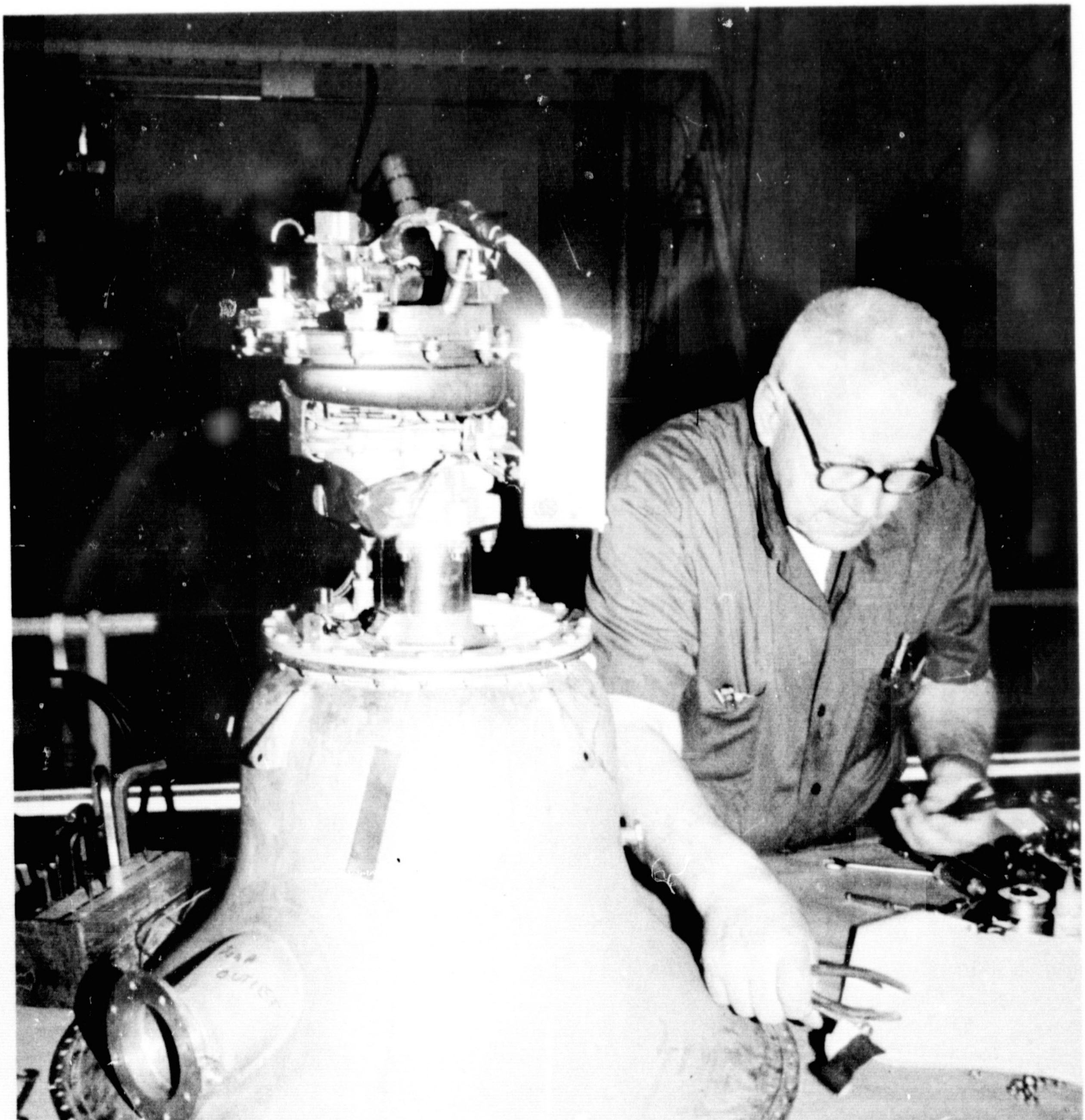


FIGURE 1 - SUMP/PUMP/TURBINE ASSEMBLY (INVERTED)

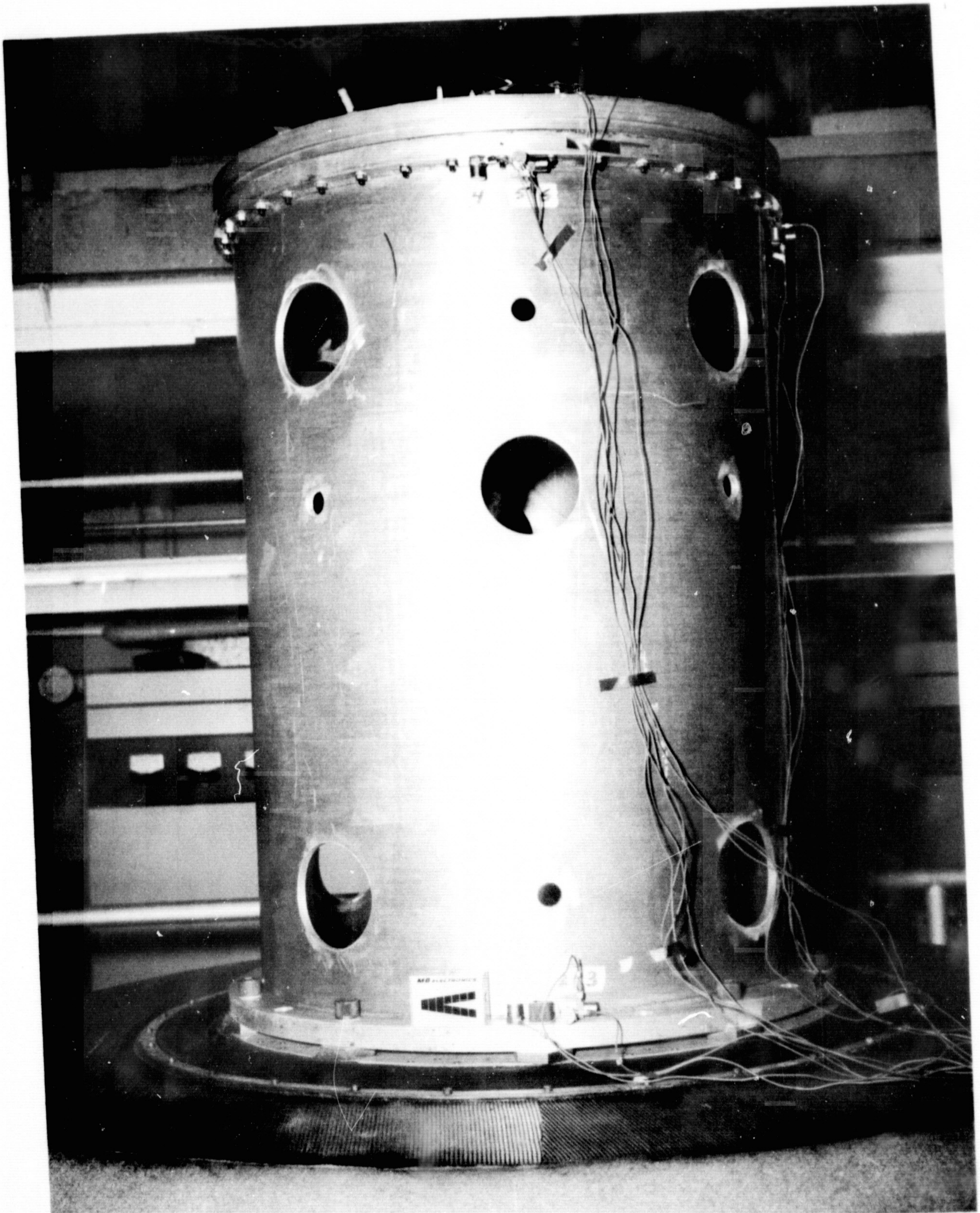


FIGURE 2 - LONGITUDINAL VIBRATION TEST SET UP

E-8427

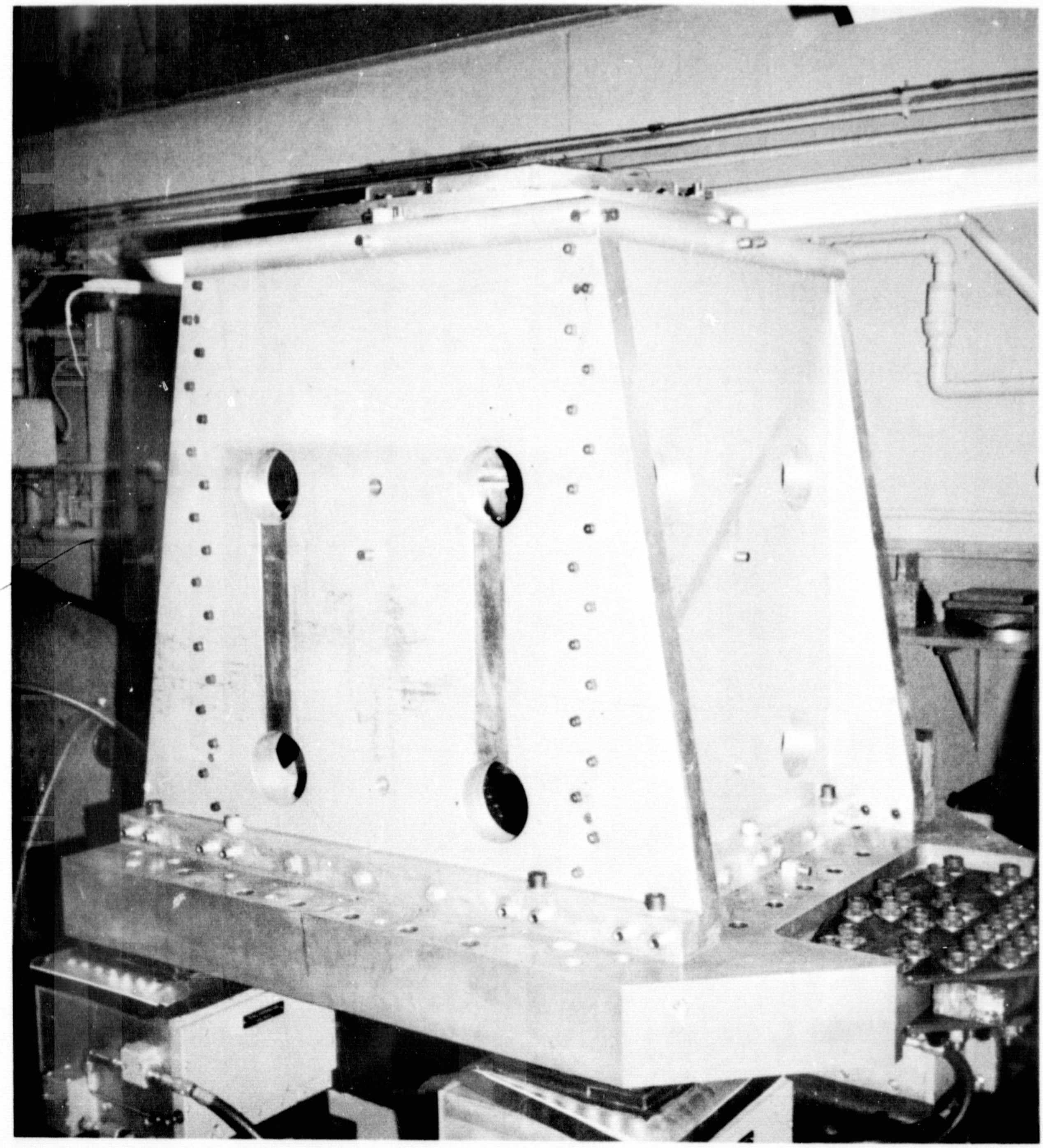


FIGURE 3 - LATERAL VIBRATION TEST SET UP

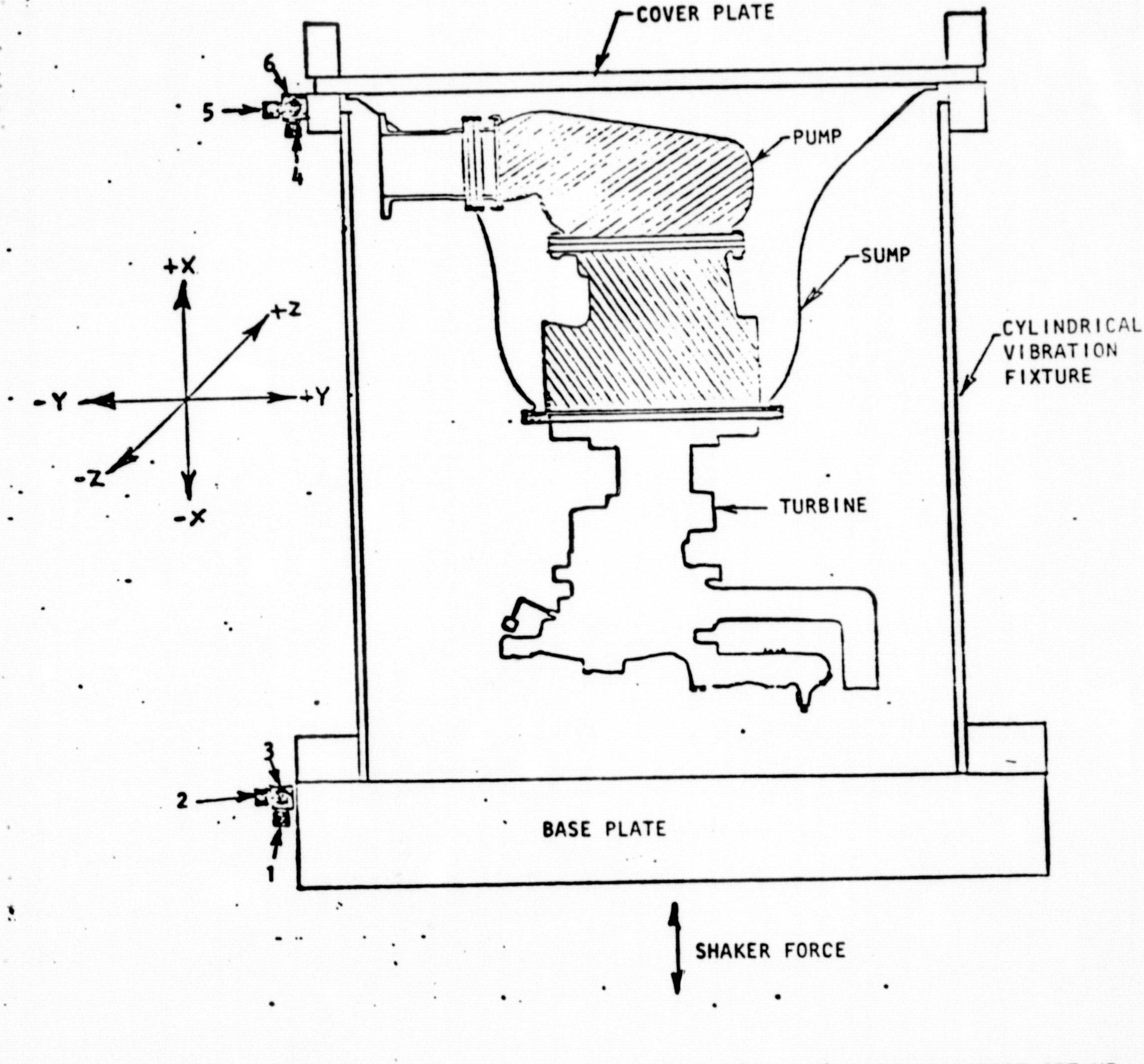
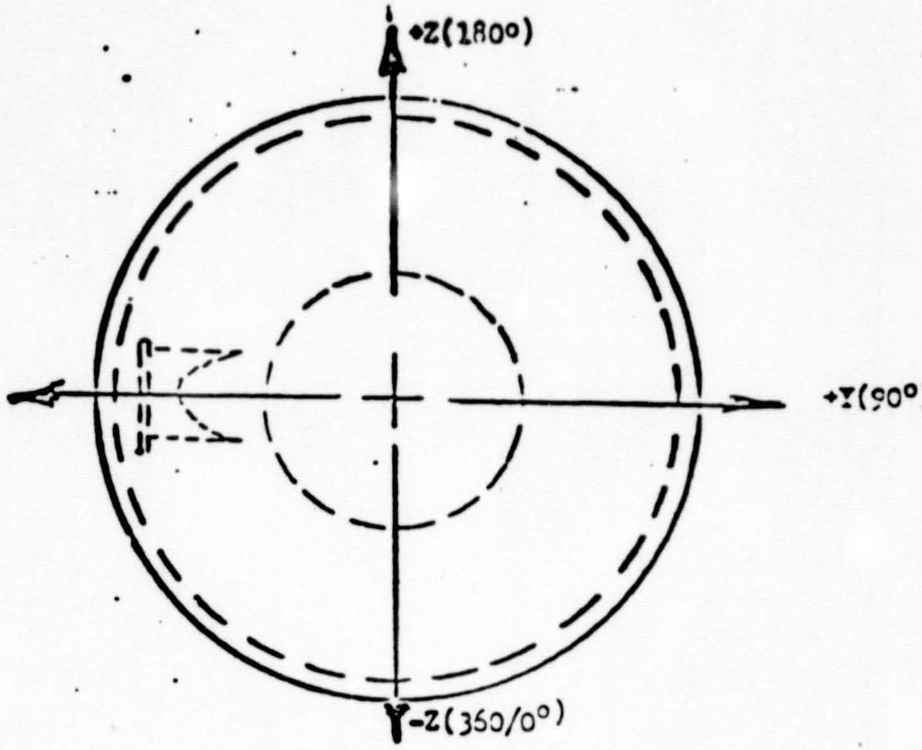
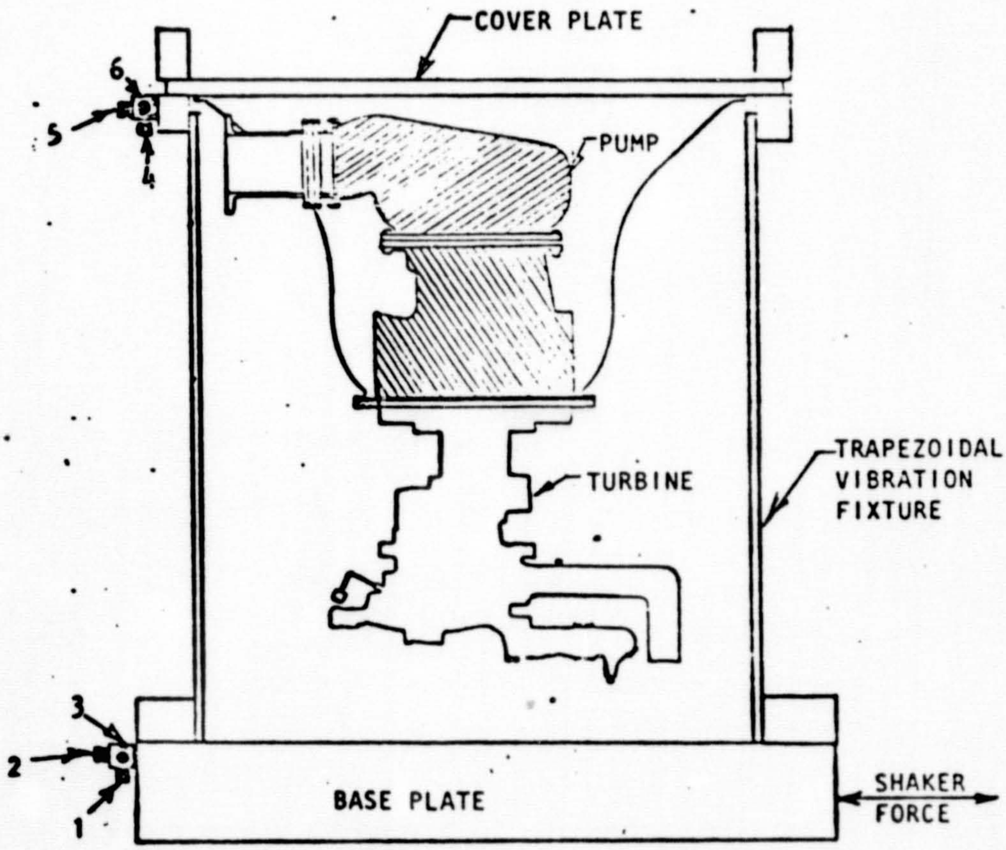


FIGURE 4 - GENERAL VIEW SHOWING LONGITUDINAL (X-AXIS) VIBRATION TEST SET UP
(THE SENSITIVITY FOR EACH ACCELEROMETER IS SHOWN IN TABLE 1)



VIEW LOOKING DOWN



(THE SENSITIVITY OF EACH ACCELEROMETER IS SHOWN IN TABLE 1)

FIGURE 5 - GENERAL VIEW SHOWING LATERAL VIBRATION TEST SET UP
Y - AXIS TEST AS SHOWN
Z - AXIS TEST ROTATE TOP FLANGE 90° clockwise

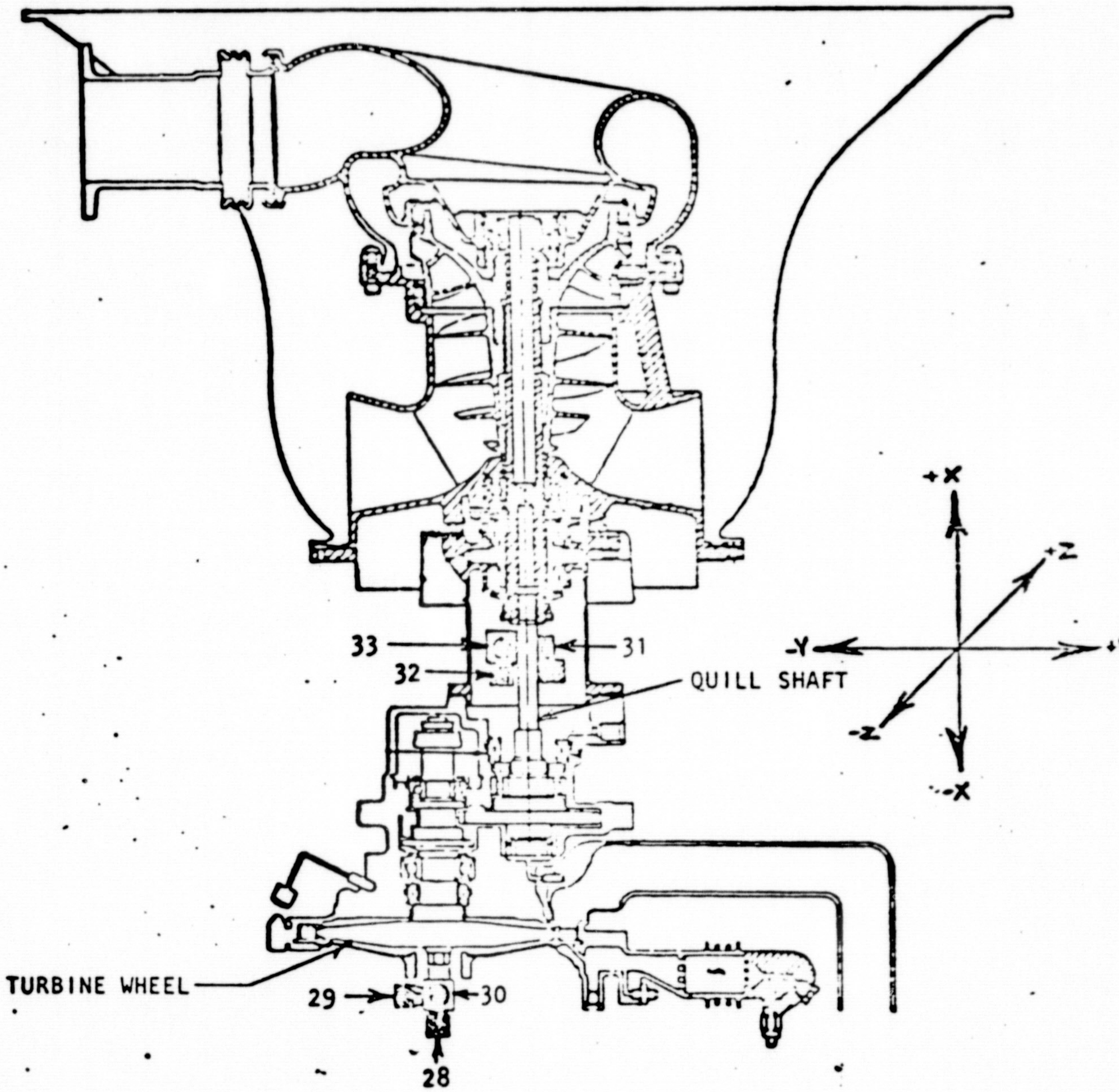


FIGURE 6 - GENERAL VIEW SHOWING LOCATION OF THE TURBINE NUT AND QUILL SHAFT ACCELEROMETERS

(THE SENSITIVITY OF EACH ACCELEROMETER IS SHOWN IN TABLE 1.)

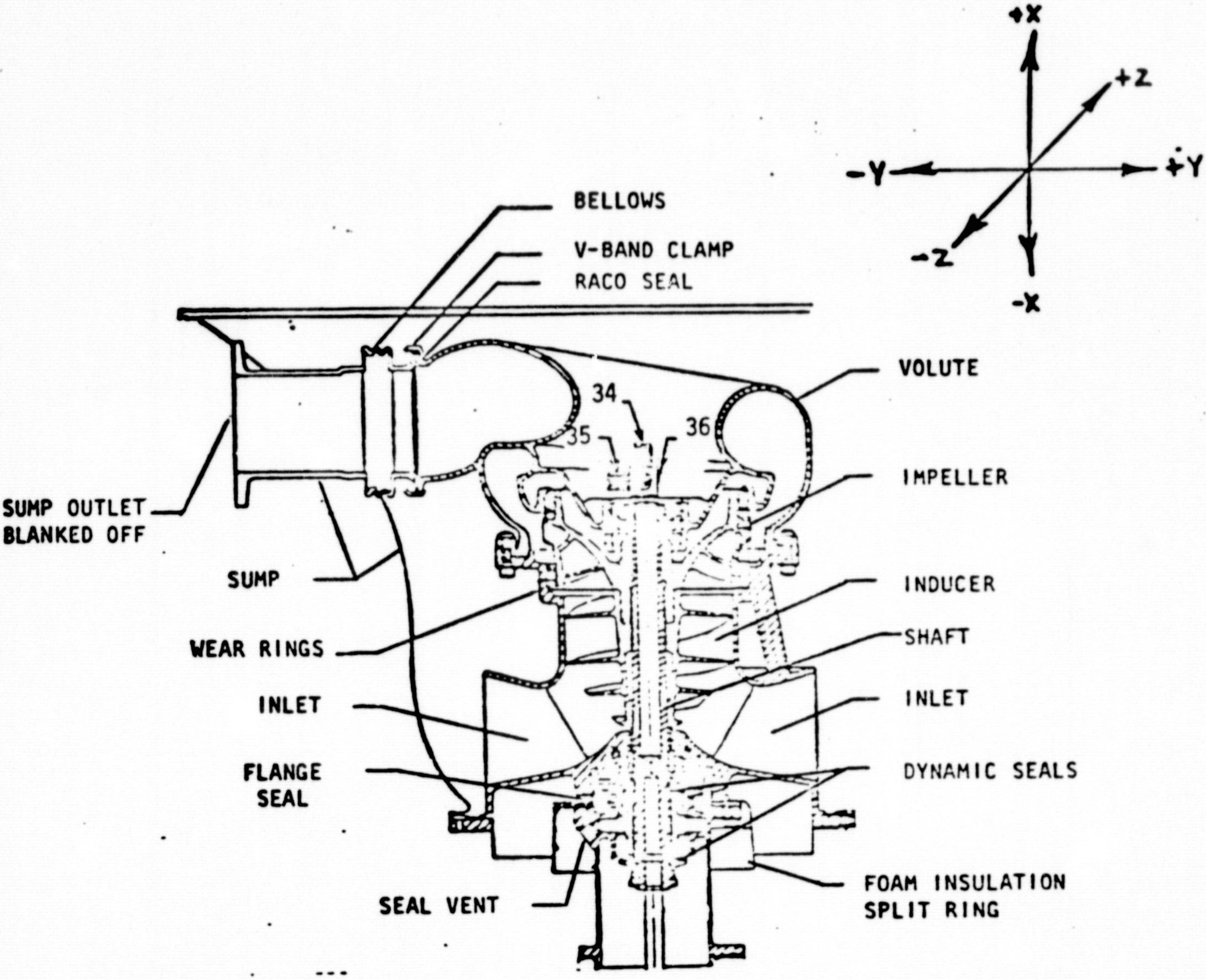


FIGURE 7 - GENERAL VIEW SHOWING LOCATION OF THE PUMP SHAFT ACCELEROMETERS
(THE SENSITIVITY OF EACH ACCELEROMETER IS SHOWN IN TABLE 1)

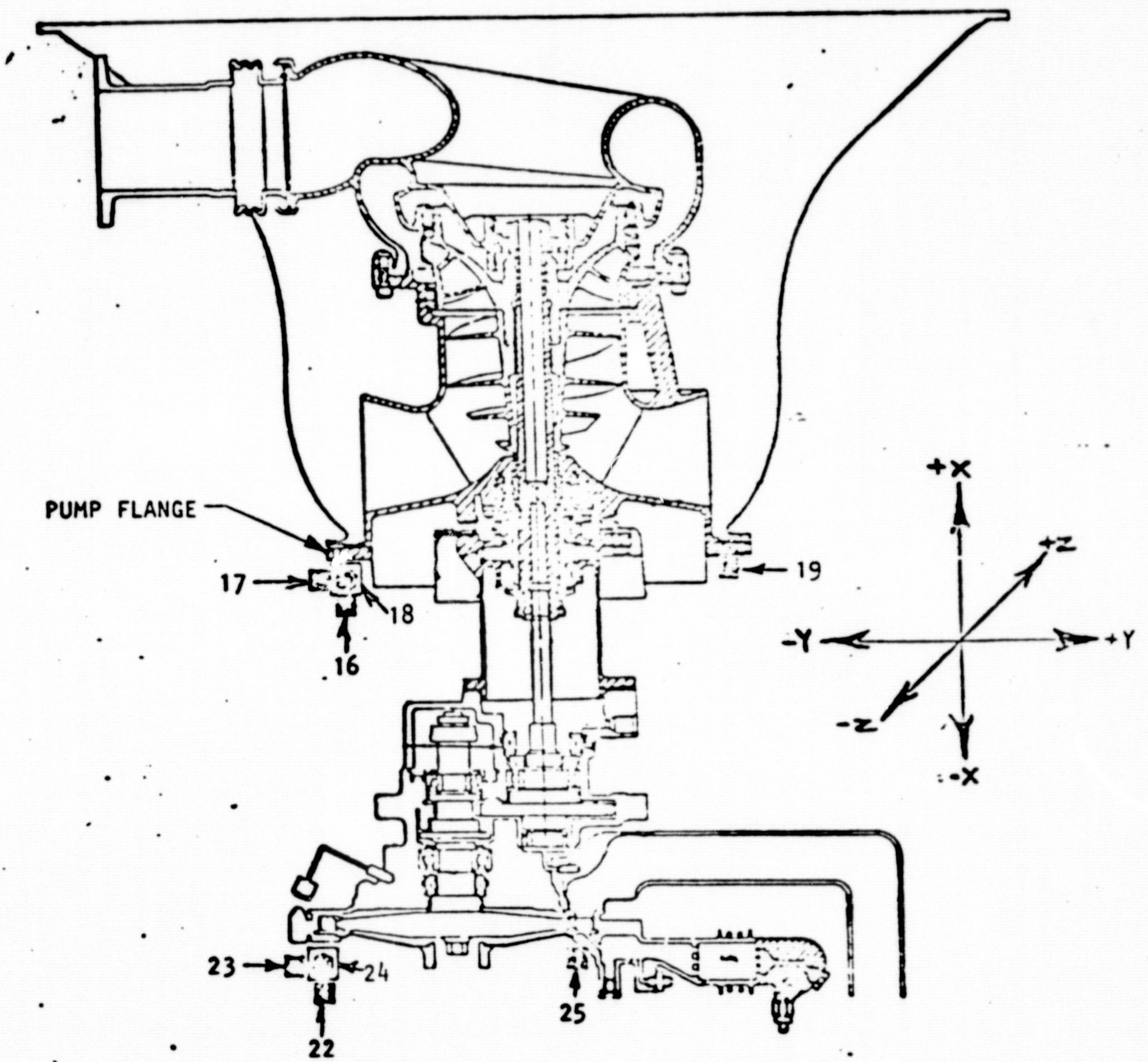


FIGURE 8 - GENERAL VIEW SHOWING LOCATION OF THE PUMP FLANGE AND TURBINE WHEEL ACCELEROMETERS

(THE SENSITIVITY OF EACH ACCELEROMETER IS SHOWN IN TABLE 1.)

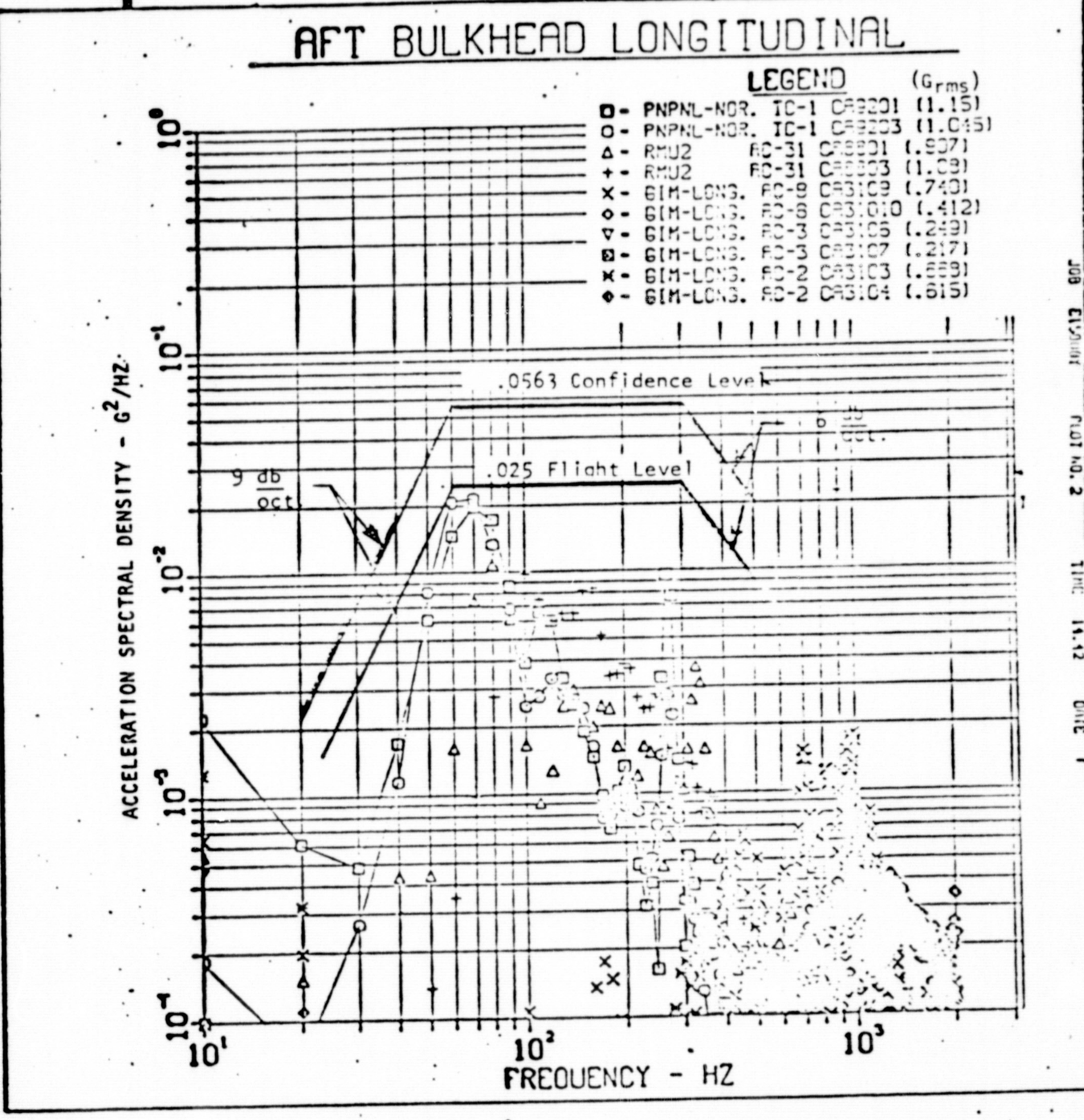
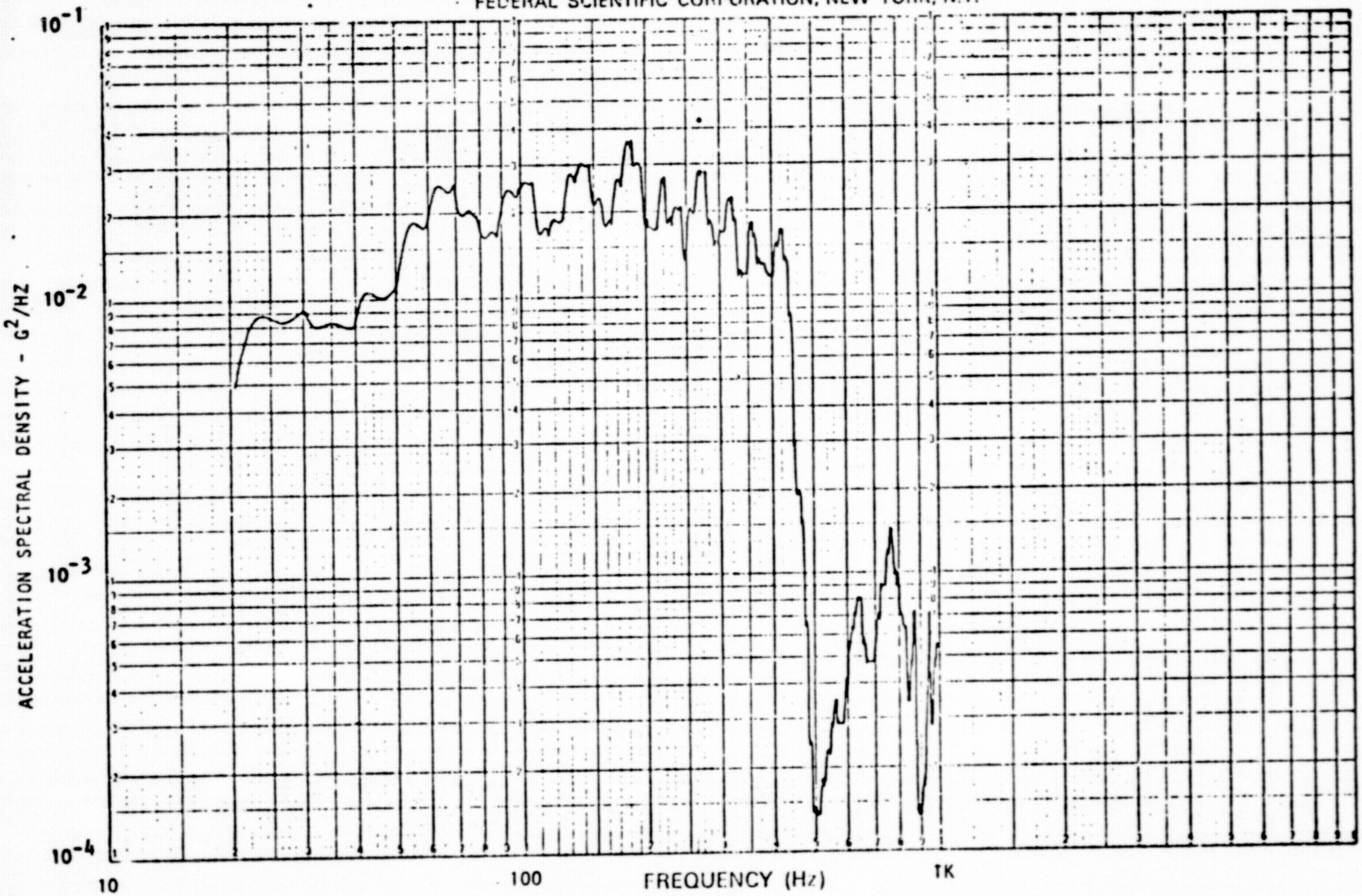


FIGURE 9a - CONFIDENCE DEMONSTRATION AND SIMULATED TC-1 FLIGHT TEST LEVELS
X-AXIS
FLIGHT LEVEL OVERALL G_{rms} = 3.06
CONFIDENCE LEVEL OVERALL G_{rms} = 4.59

FIGURE 9b - ACTUAL TEST LEVELS FOR SIMULATED TC-1 FLIGHT LEVELS
X-AXIS

FEDERAL SCIENTIFIC CORPORATION, NEW YORK, N.Y.



Project No. Item Serial No. Date Time

Conditions Pickup Serial No. & Location Pickup Sensitivity

Recorder Reproducer Reproduce tape speed ips FM/direct Track No.

Ubiquitous ® Processor Input Attenuator Output Gain Analysis Range Hz β= Hz

Digital Averager Overall G_{rms} = 3.1 Vertical Sensitivity Averaging Time Sec N=

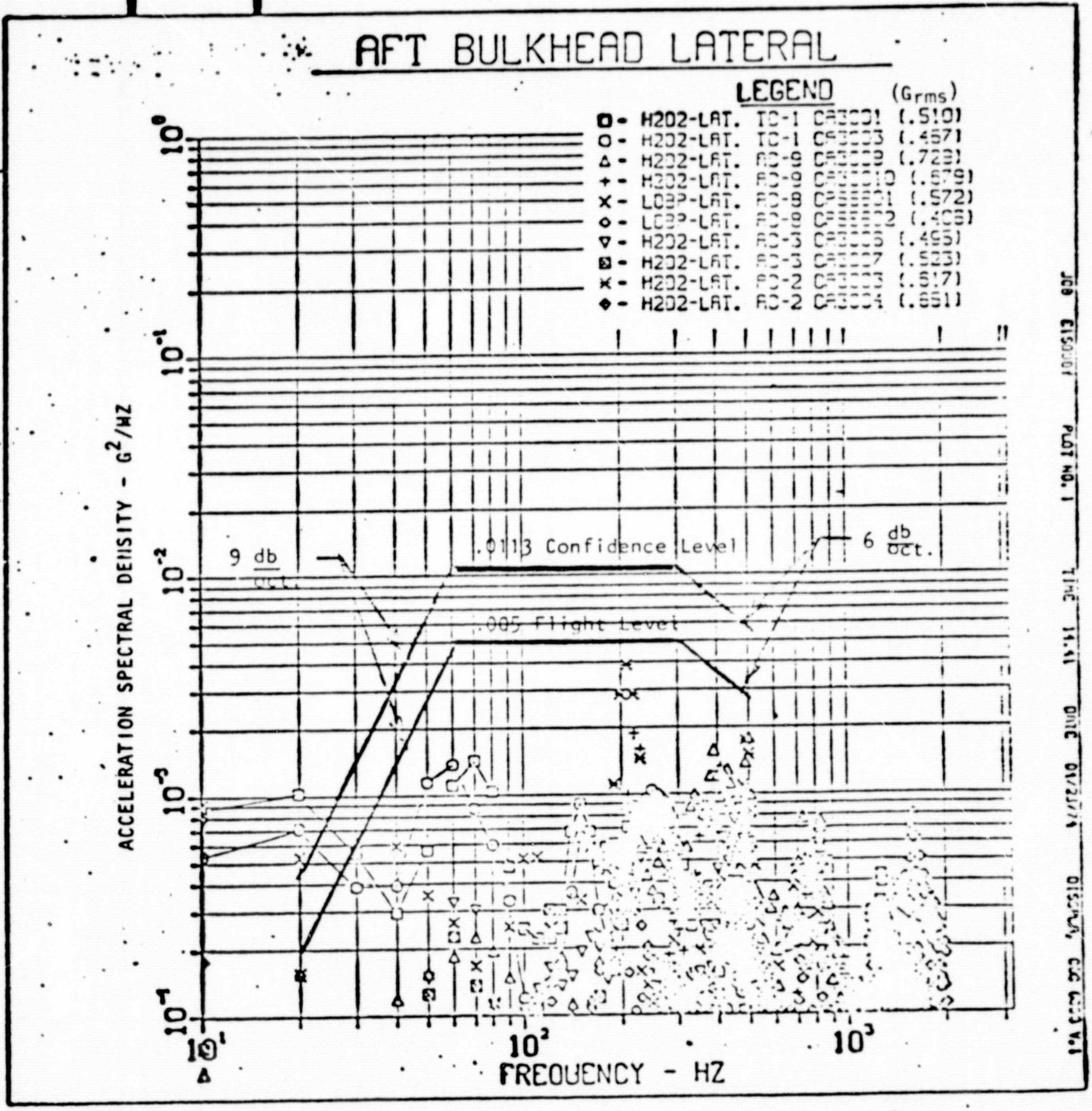


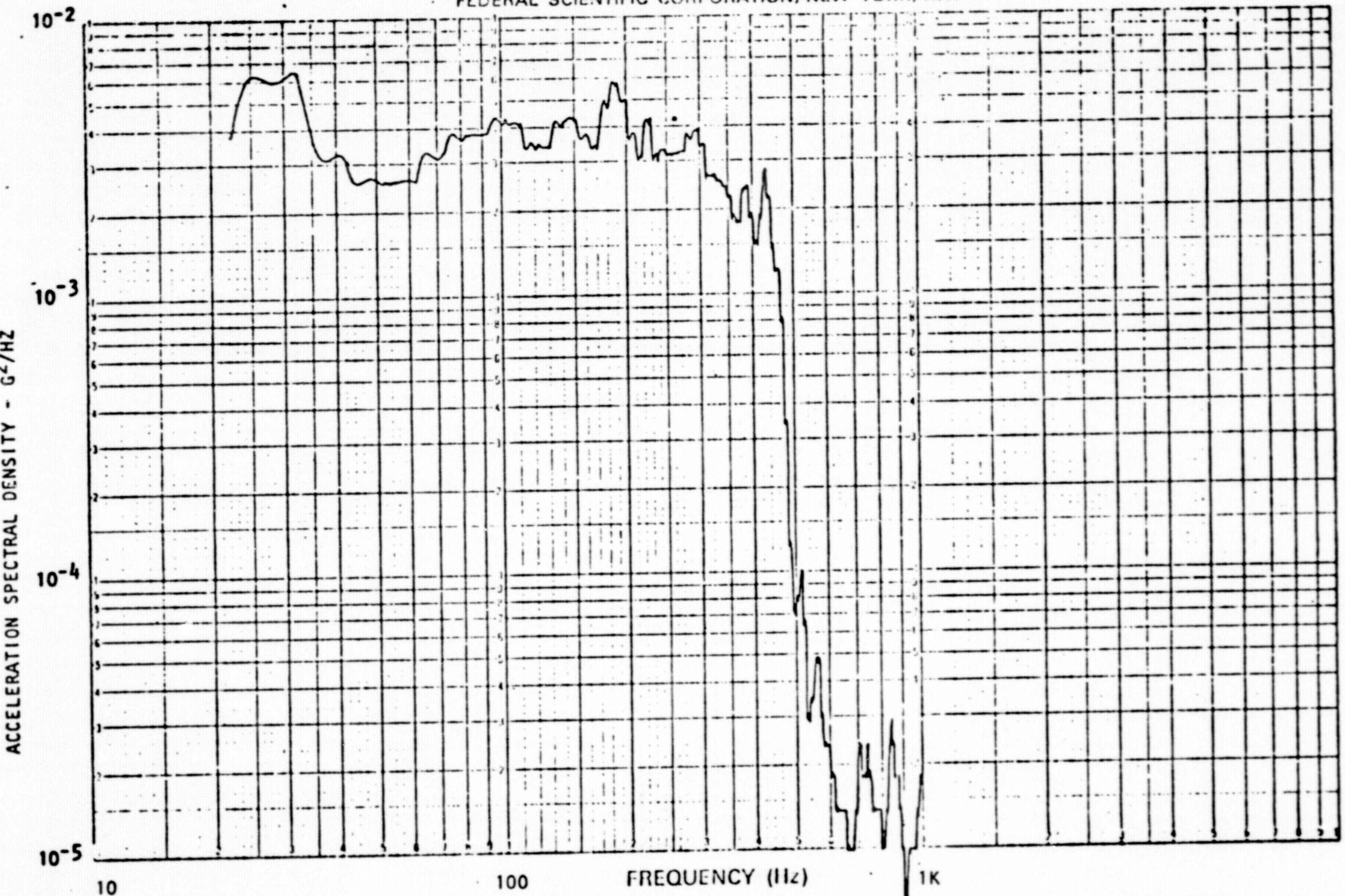
FIGURE 10a - CONFIDENCE DEMONSTRATION AND SIMULATED TC-1 FLIGHT TEST LEVELS Y AND Z AXES

FLIGHT LEVEL OVERALL G_{rms} = 1.37

CONFIDENCE LEVEL OVERALL G_{rms} = 2.06

FIGURE 10b - ACTUAL TEST LEVELS FOR SIMULATED TC-1 FLIGHT LEVELS
Y AND Z AXES

FEDERAL SCIENTIFIC CORPORATION, NEW YORK, N.Y.



Project No. .... Item .... Serial No. .... Date .... Time ....

Conditions .... Pickup Serial No. & Location .... Pickup Sensitivity ....

Recorder Reproducer .... Reproduce tape speed .... ips FM/direct Track No. ....

Ubiquitous ® Processor .... Input Attenuator .... Output Gain .... Analysis Range .... Hz β= .... Hz

Digital Averager Overall G_{rms} = 1.25 Vertical Sensitivity .... Averaging Time .... Sec N= ....

11

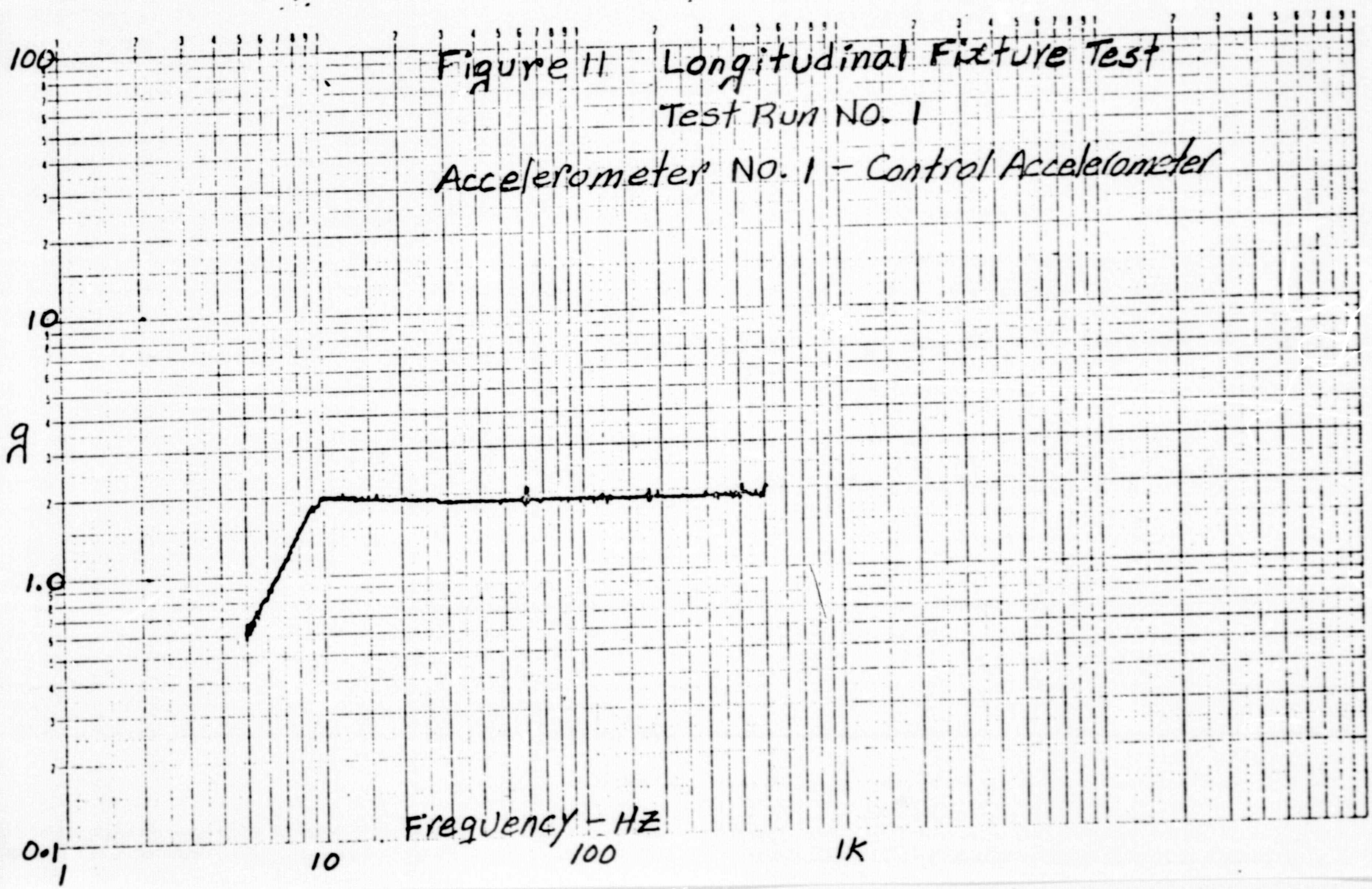
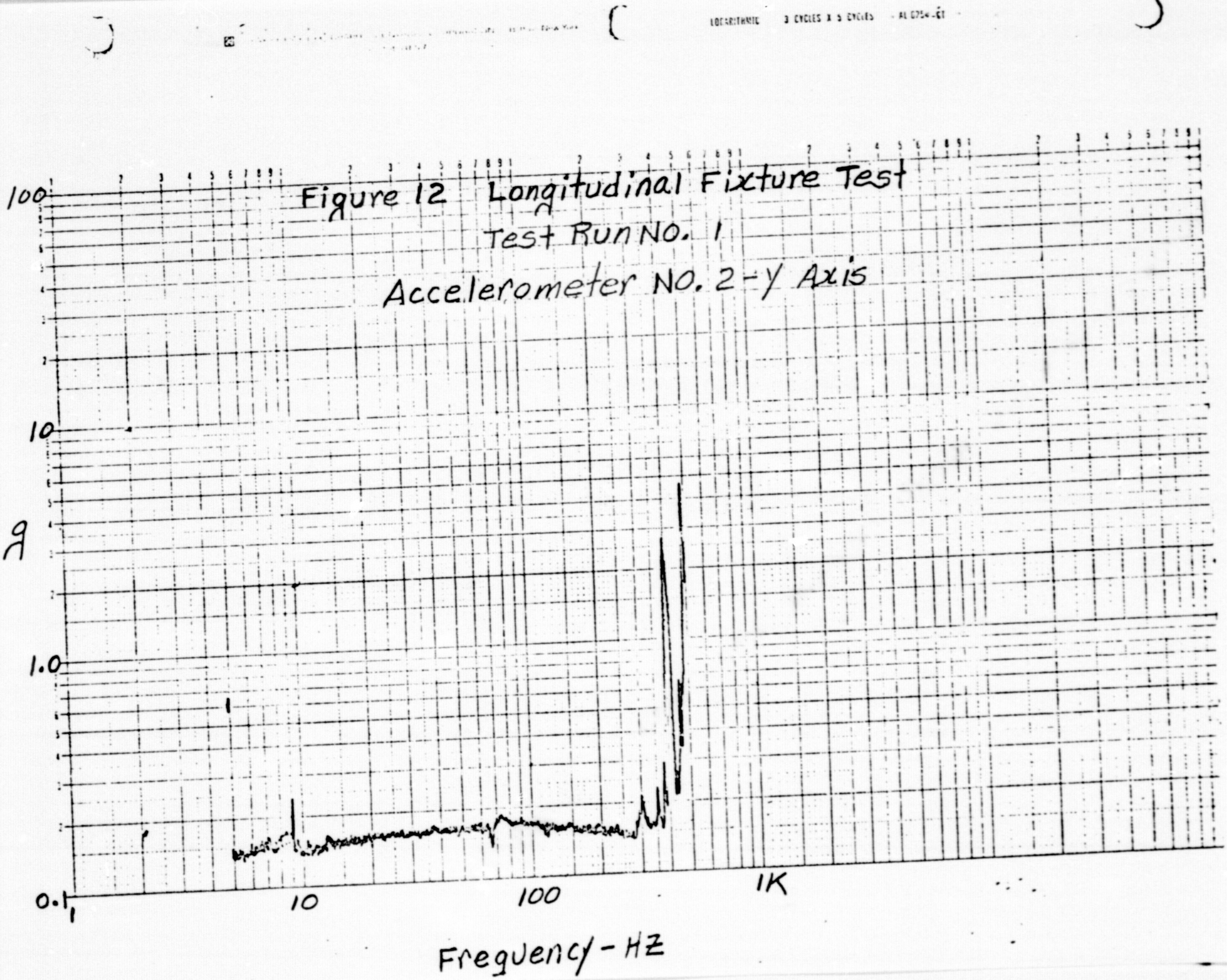


Figure 11 Longitudinal Fixture Test
Test Run NO. 1
Accelerometer NO. 1 - Control Accelerometer
g
100
10
1.0
0.1
1
10
100
1K
Frequency - HZ
LOGARITHMIC 3 CYCLES X 5 CYCLES


LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 12 Longitudinal Fixture Test
Test Run NO. 1
Accelerometer NO. 2-Y Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ

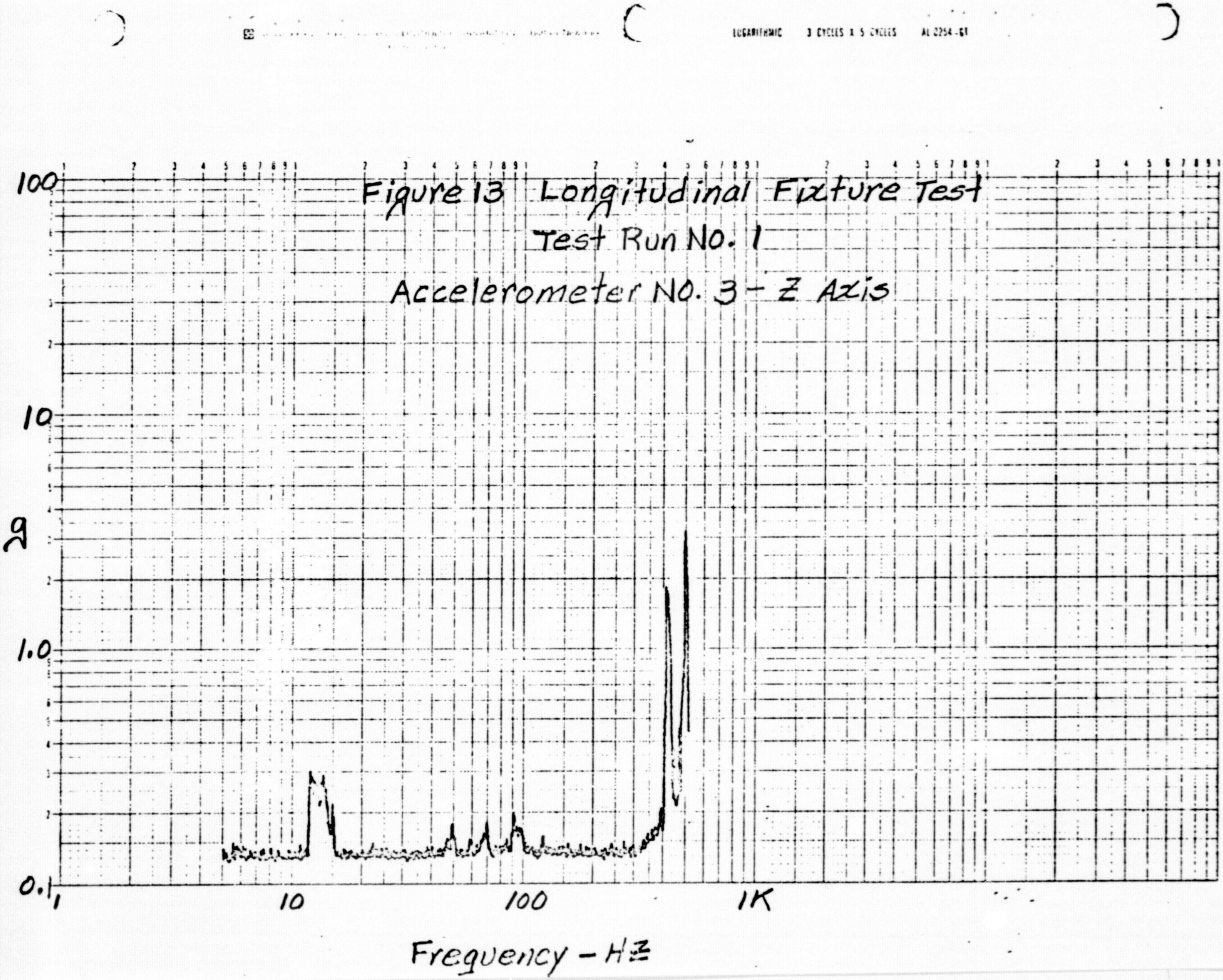


Figure 13 Longitudinal Fixture Test
Test Run No. 1
Accelerometer No. 3 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz
LOGARITHMIC 3 CYCLES X 5 CYCLES

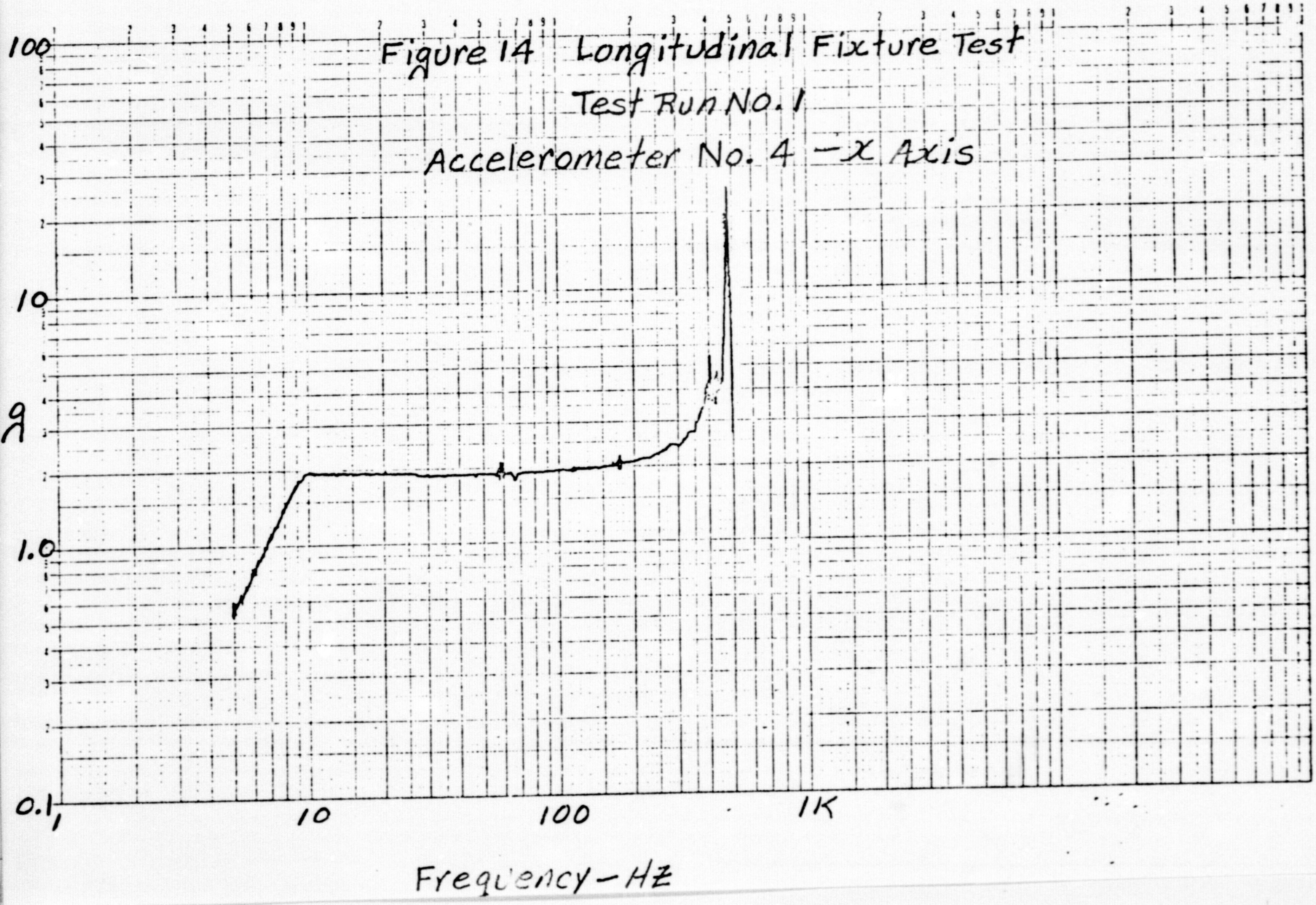
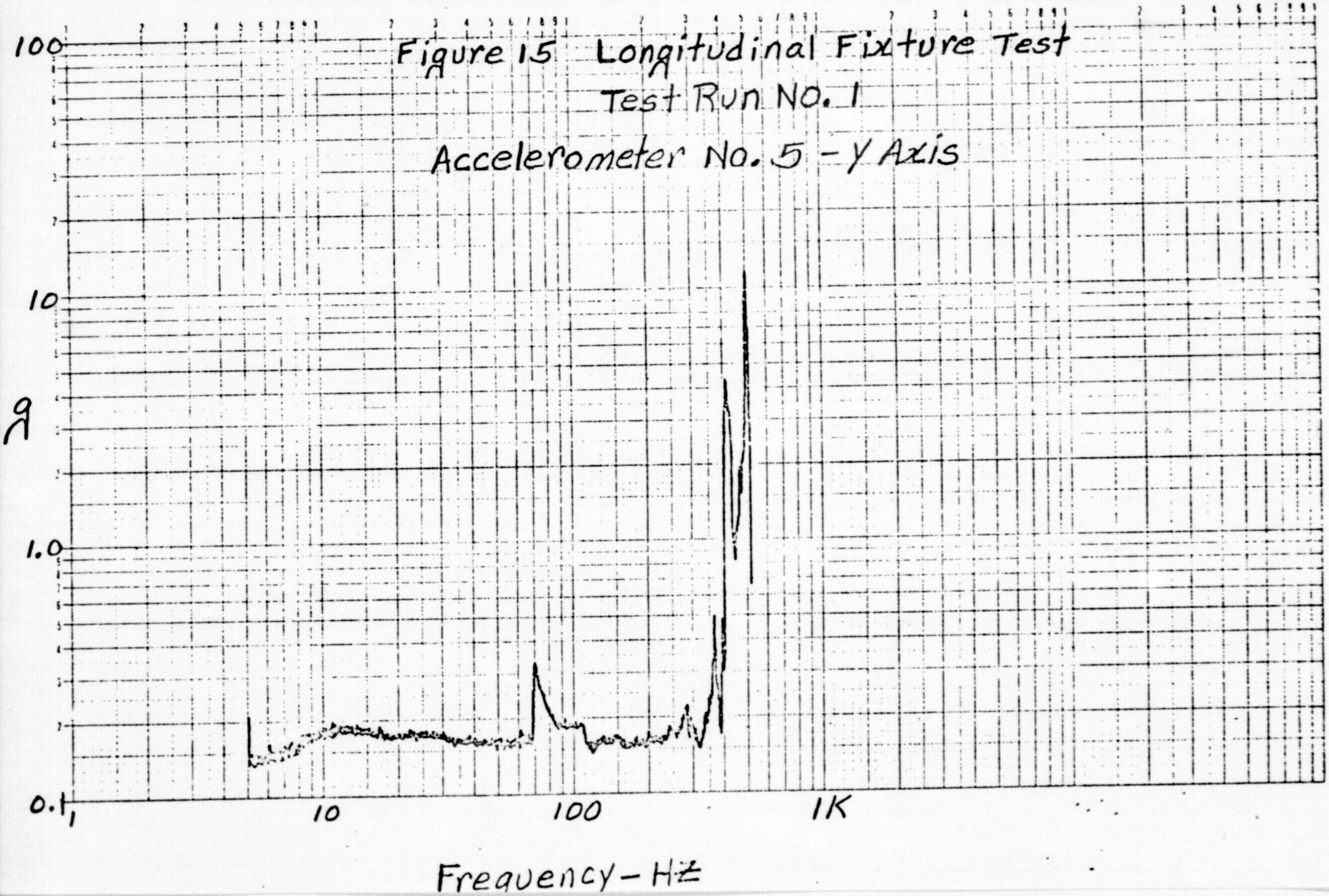


Figure 14 Longitudinal Fixture Test
Test Run No. 1
Accelerometer No. 4 -x Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency-HZ

LOGARITHMIC 3 CYCLES X 5 CYCLES AL 0734-61

Figure 15 Longitudinal Fixture Test
Test Run No. 1
Accelerometer No. 5 - Y Axis



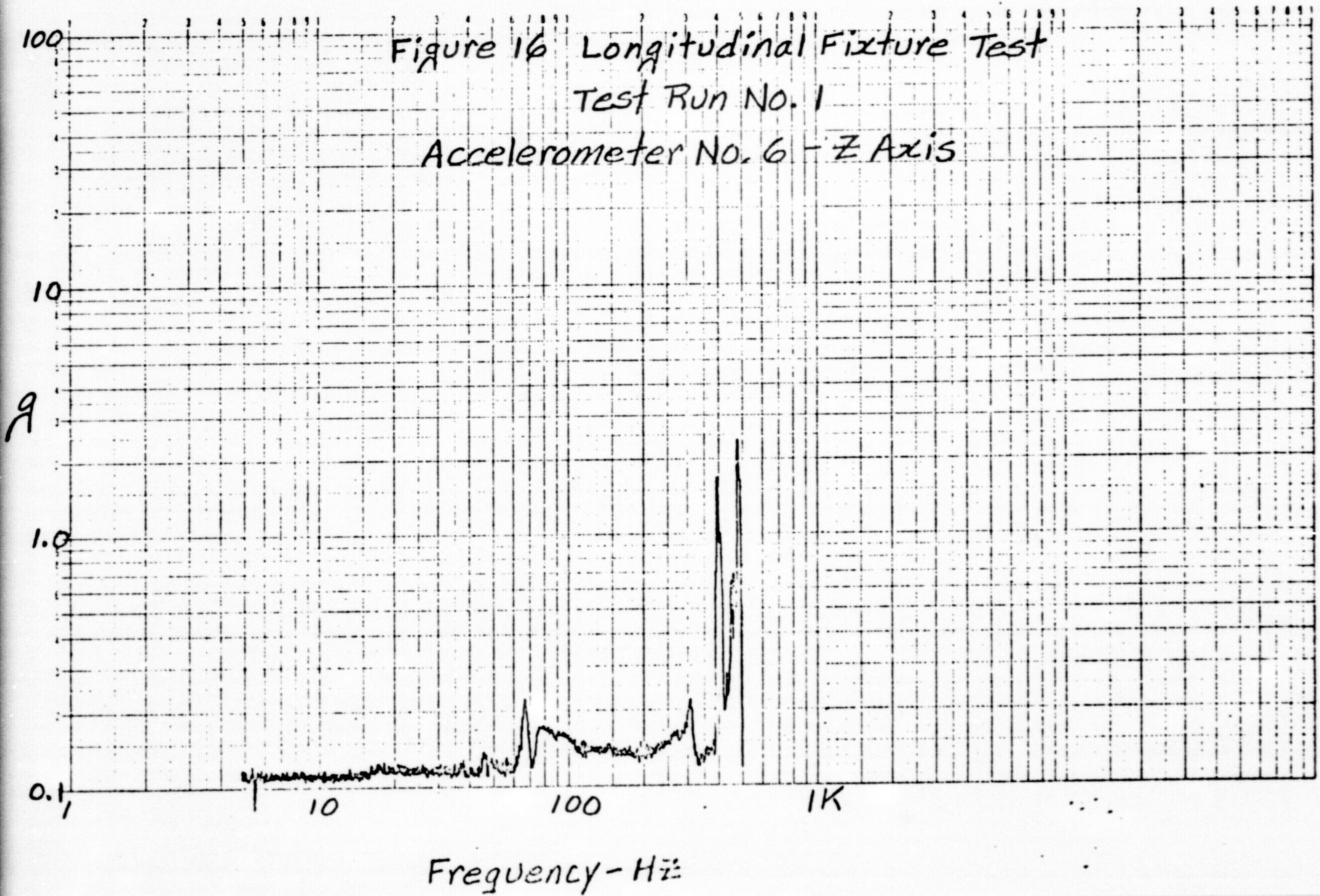


Figure 16 Longitudinal Fixture Test
Test Run No. 1
Accelerometer No. 6 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

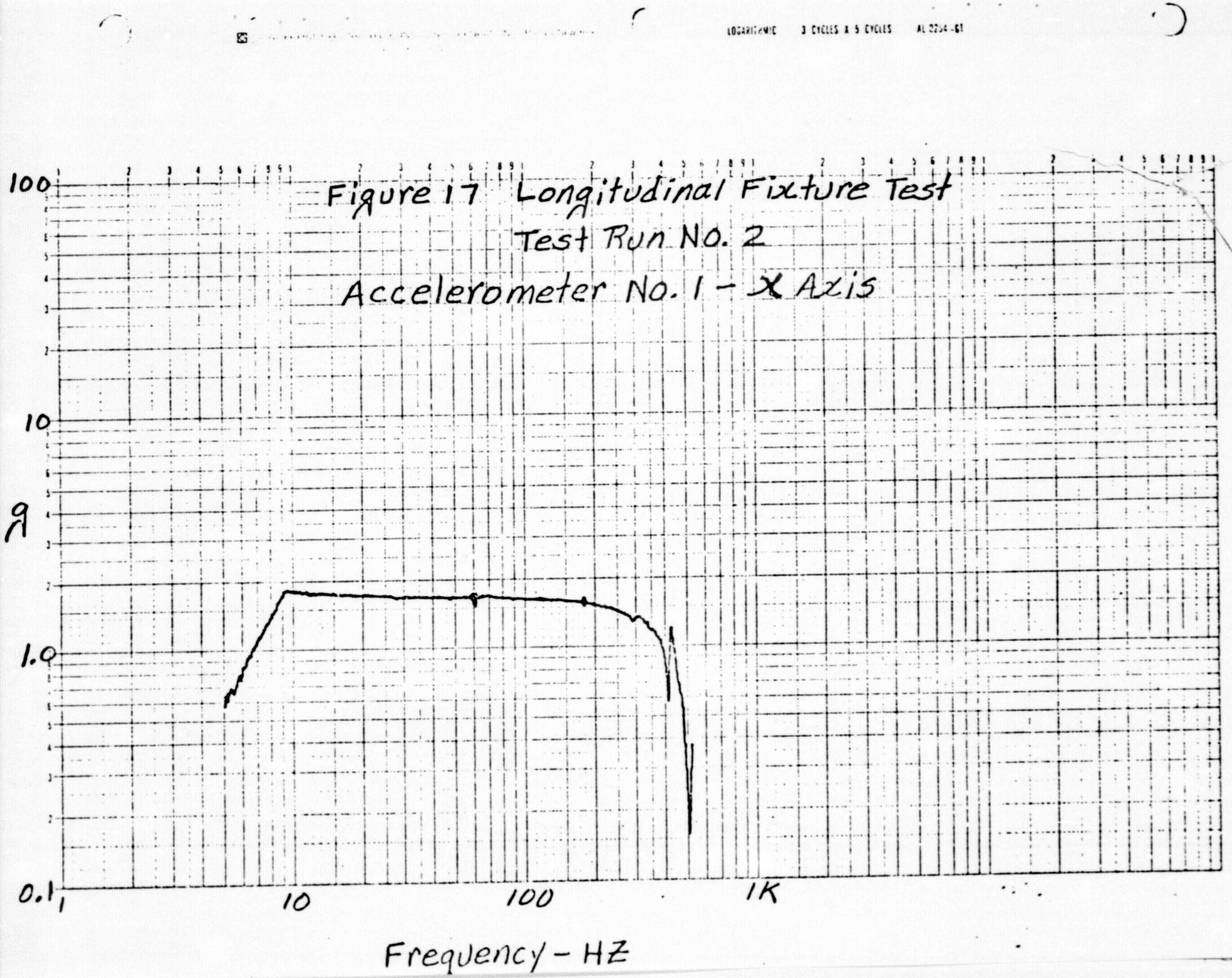


Figure 17 Longitudinal Fixture Test
Test Run No. 2
Accelerometer No. 1 - X Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

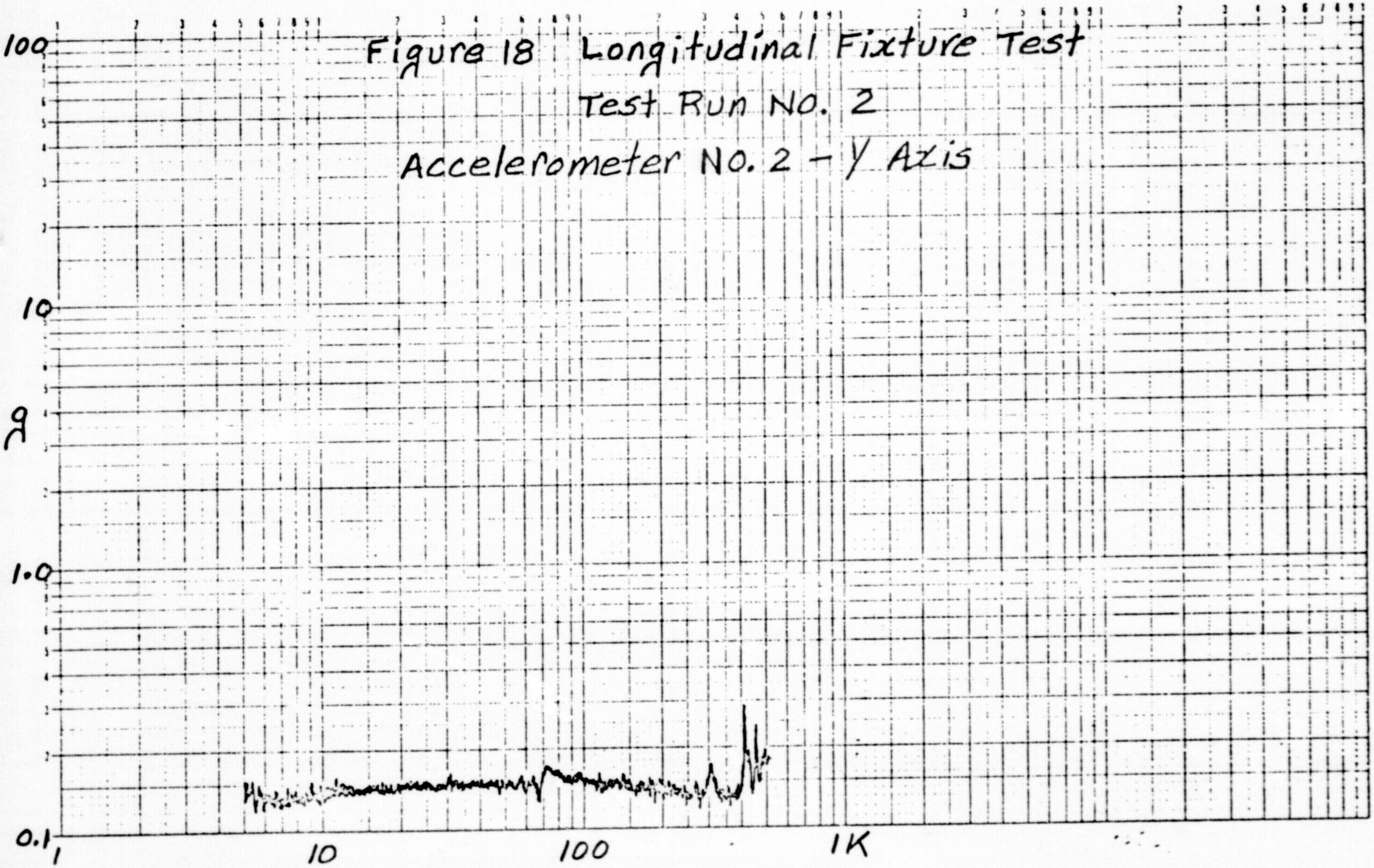


Figure 18 Longitudinal Fixture Test
Test Run No. 2
Accelerometer No. 2 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K

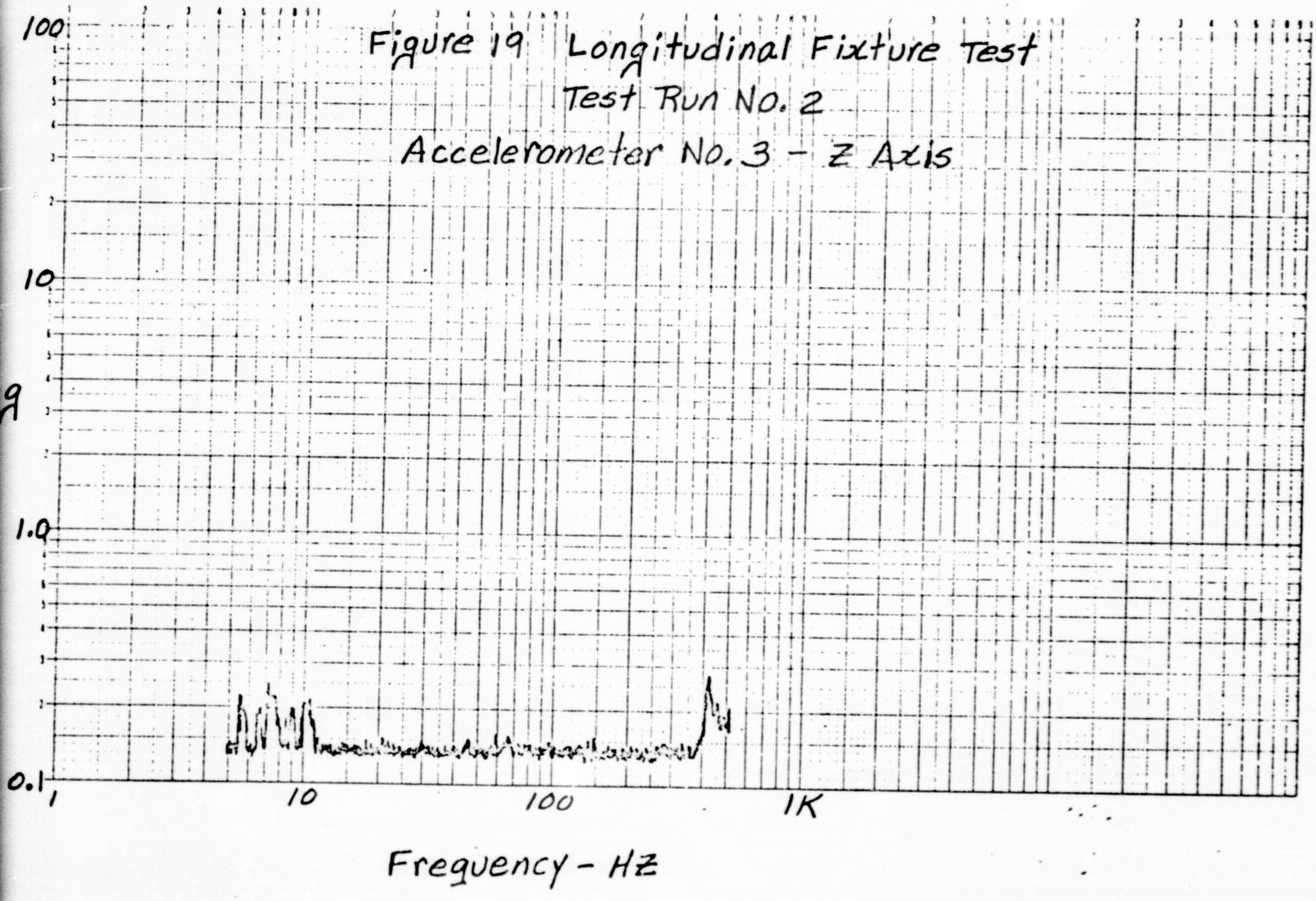


Figure 19 Longitudinal Fixture Test
Test Run No. 2
Accelerometer No. 3 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

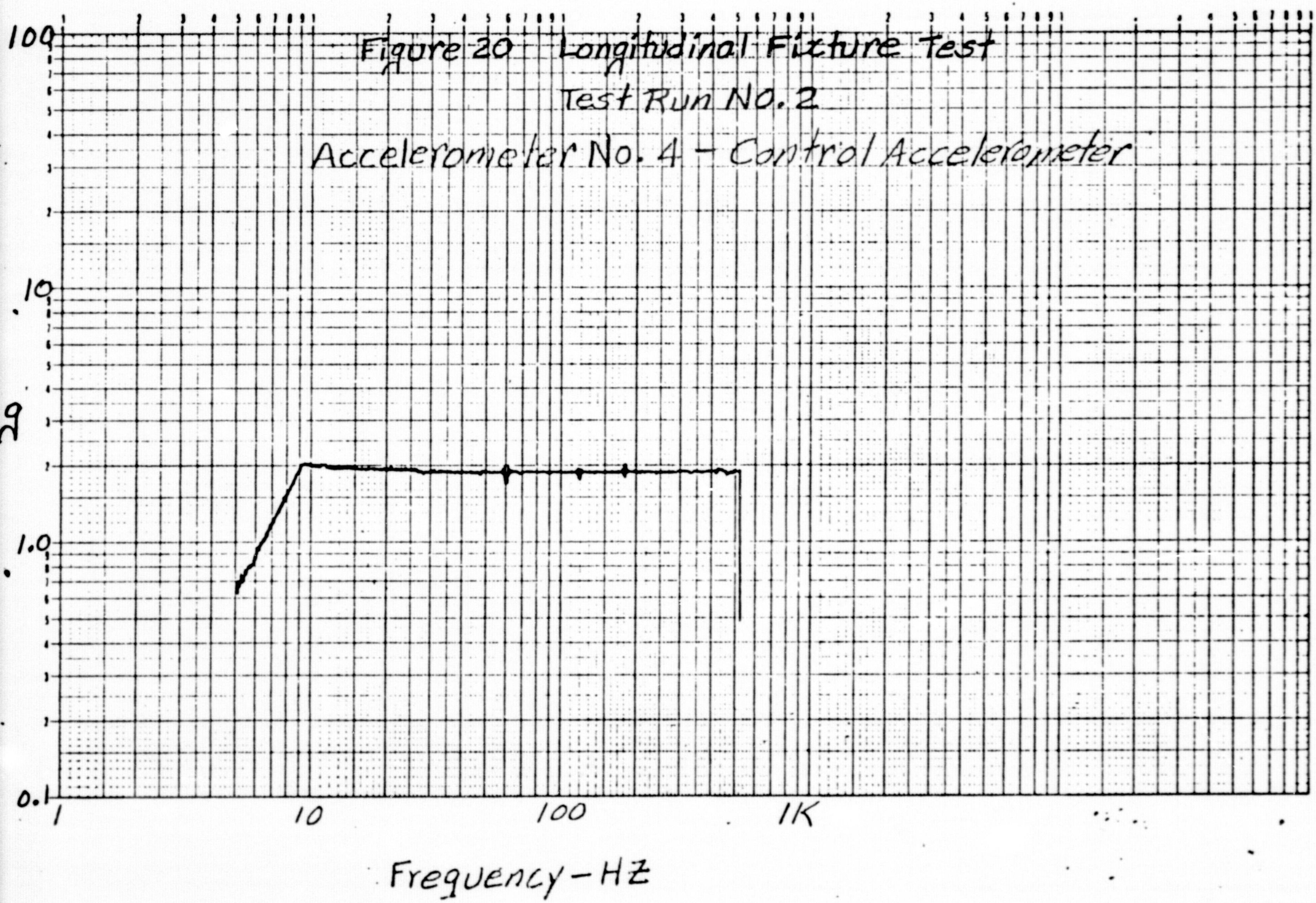


Figure 20 Longitudinal Fixture Test
Test Run No. 2
Accelerometer No. 4 - Control Accelerometer
100
10
1.0
0.1
g
1
10
100
1K
Frequency-HZ

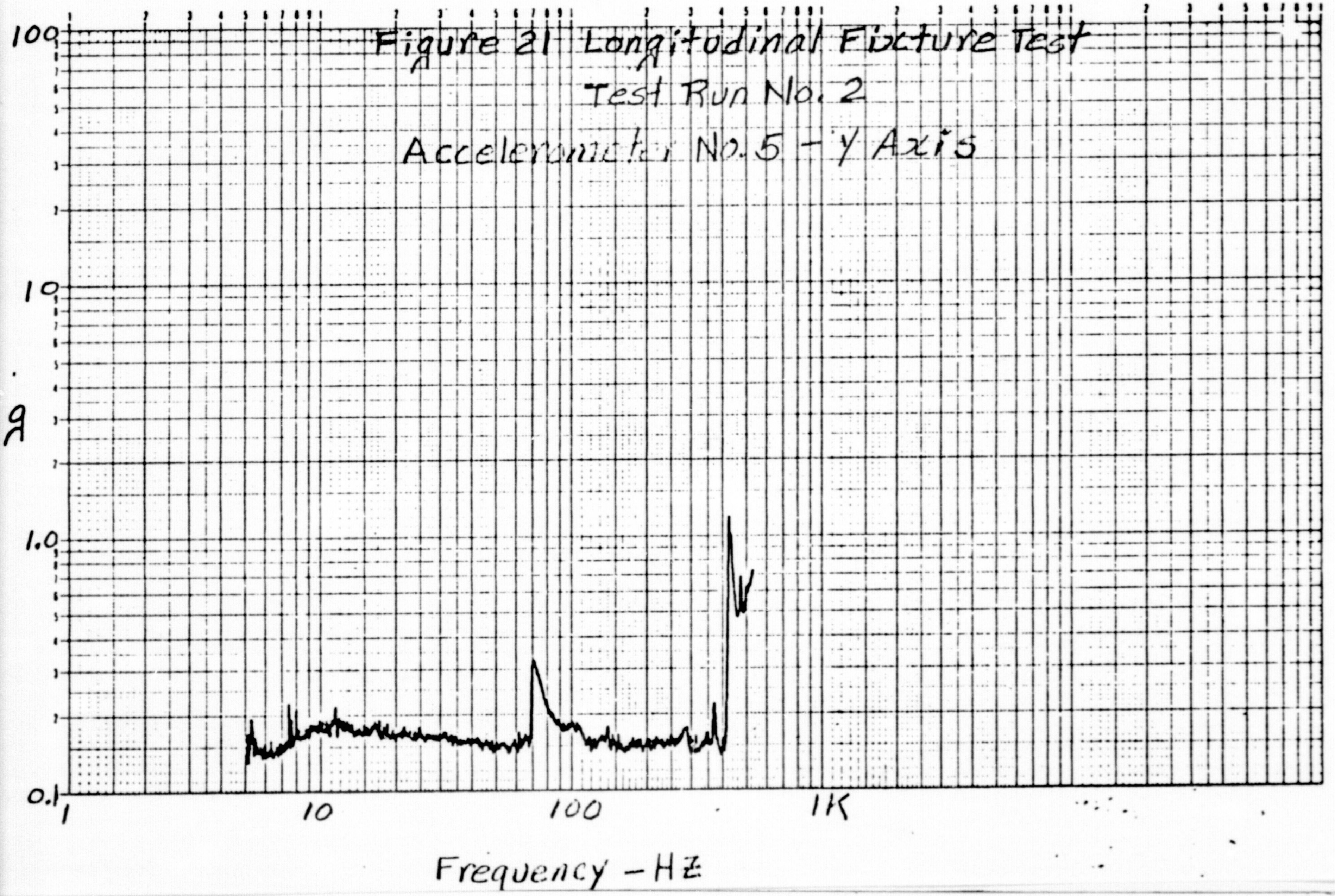


Figure 21 Longitudinal Fixture Test
Test Run No. 2
Accelerometer No. 5 - Y Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ

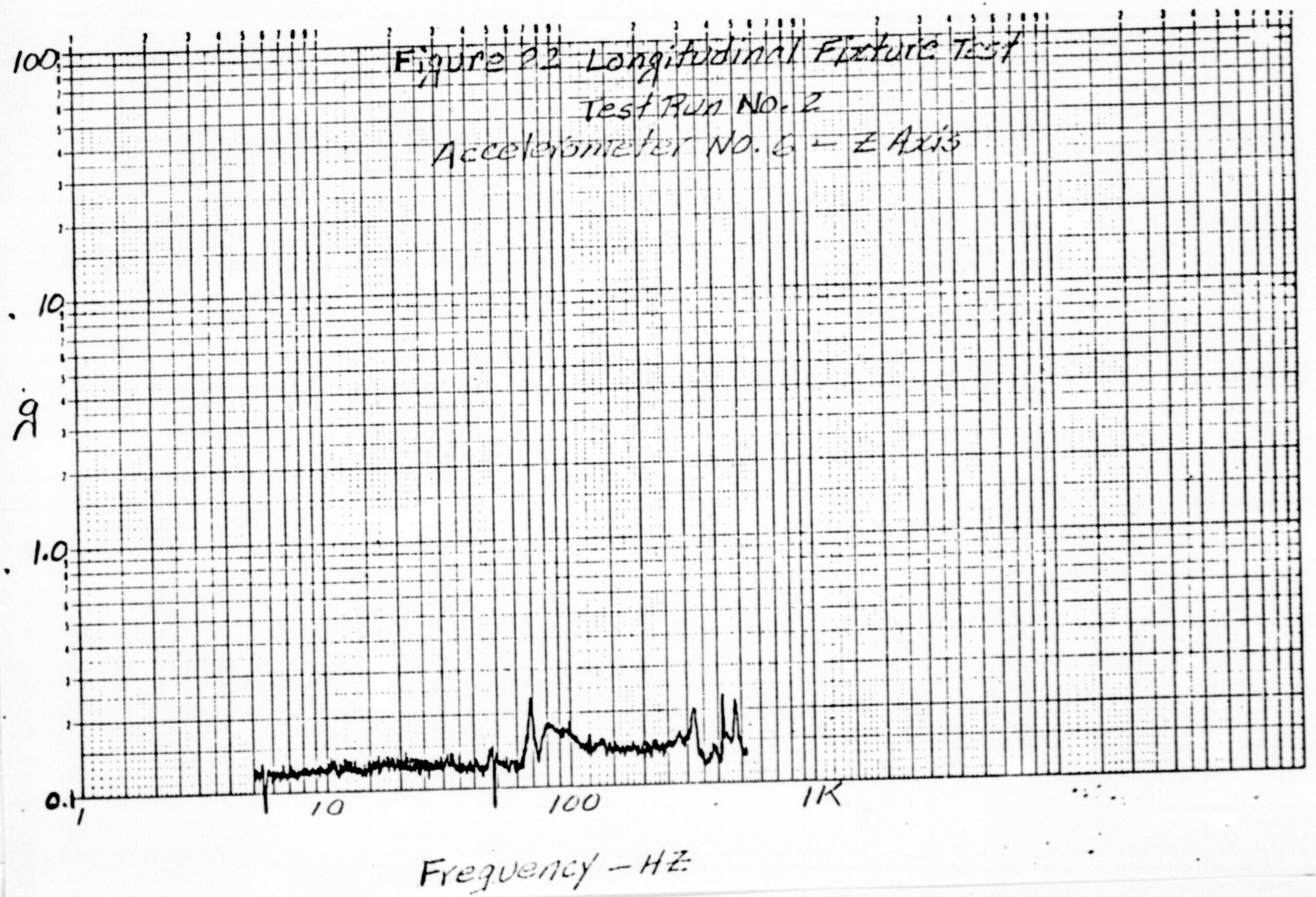


Figure 22 Longitudinal Fixture Test
Test Run No. 2
Accelerometer No. 6 – Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency – HZ

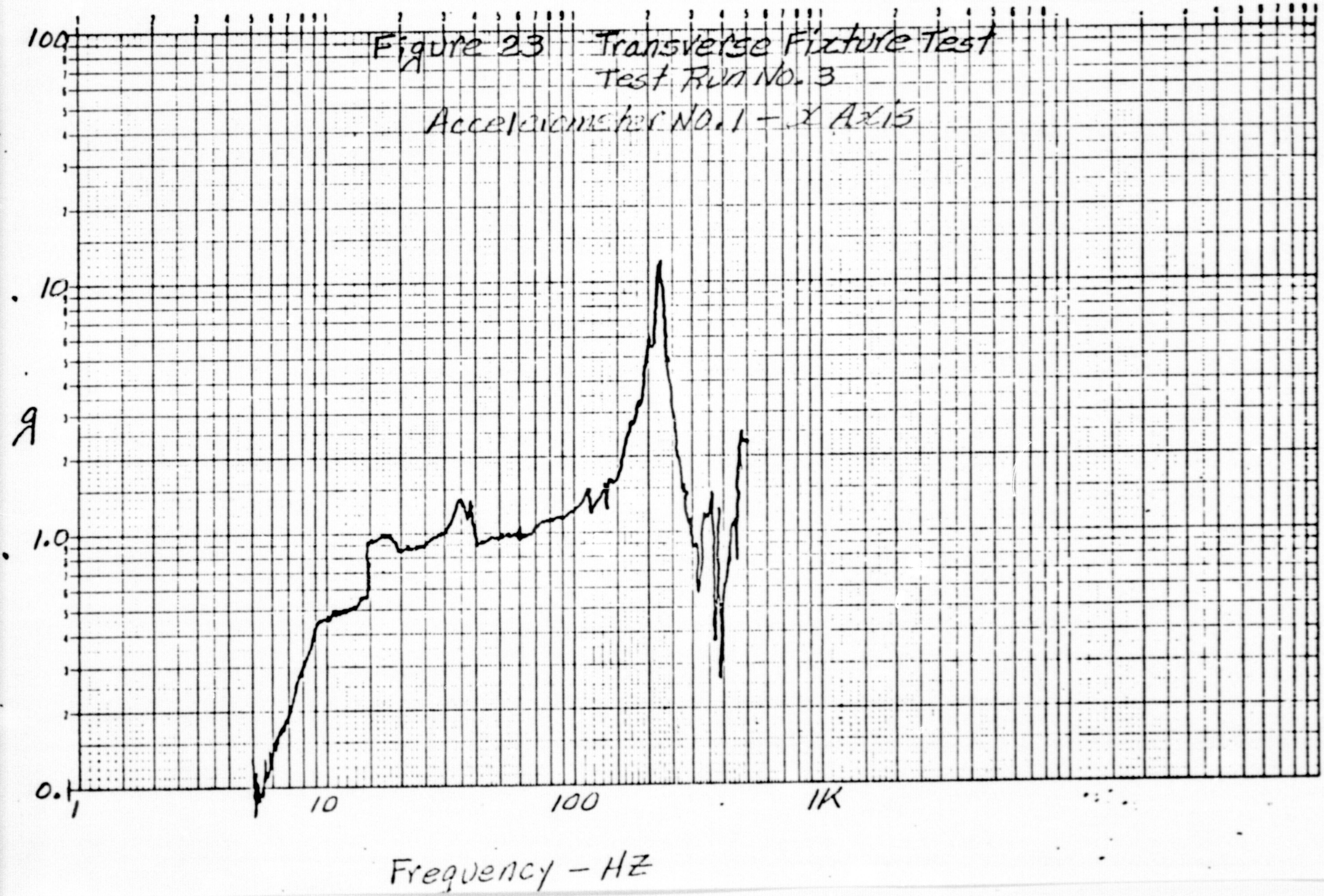


Figure 23 Transverse Fixture Test
Test Run No. 3
Accelerometer No. 1 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ

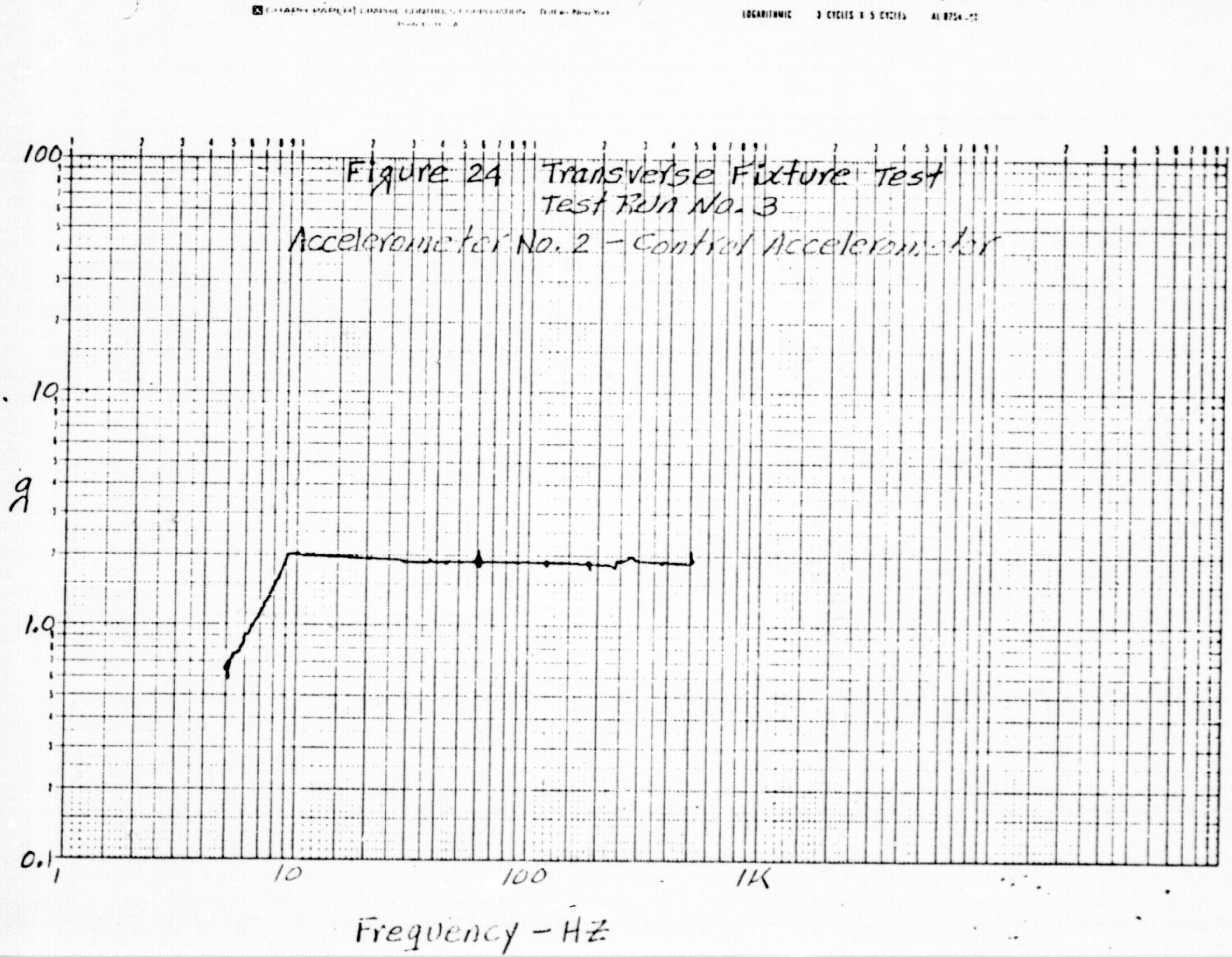
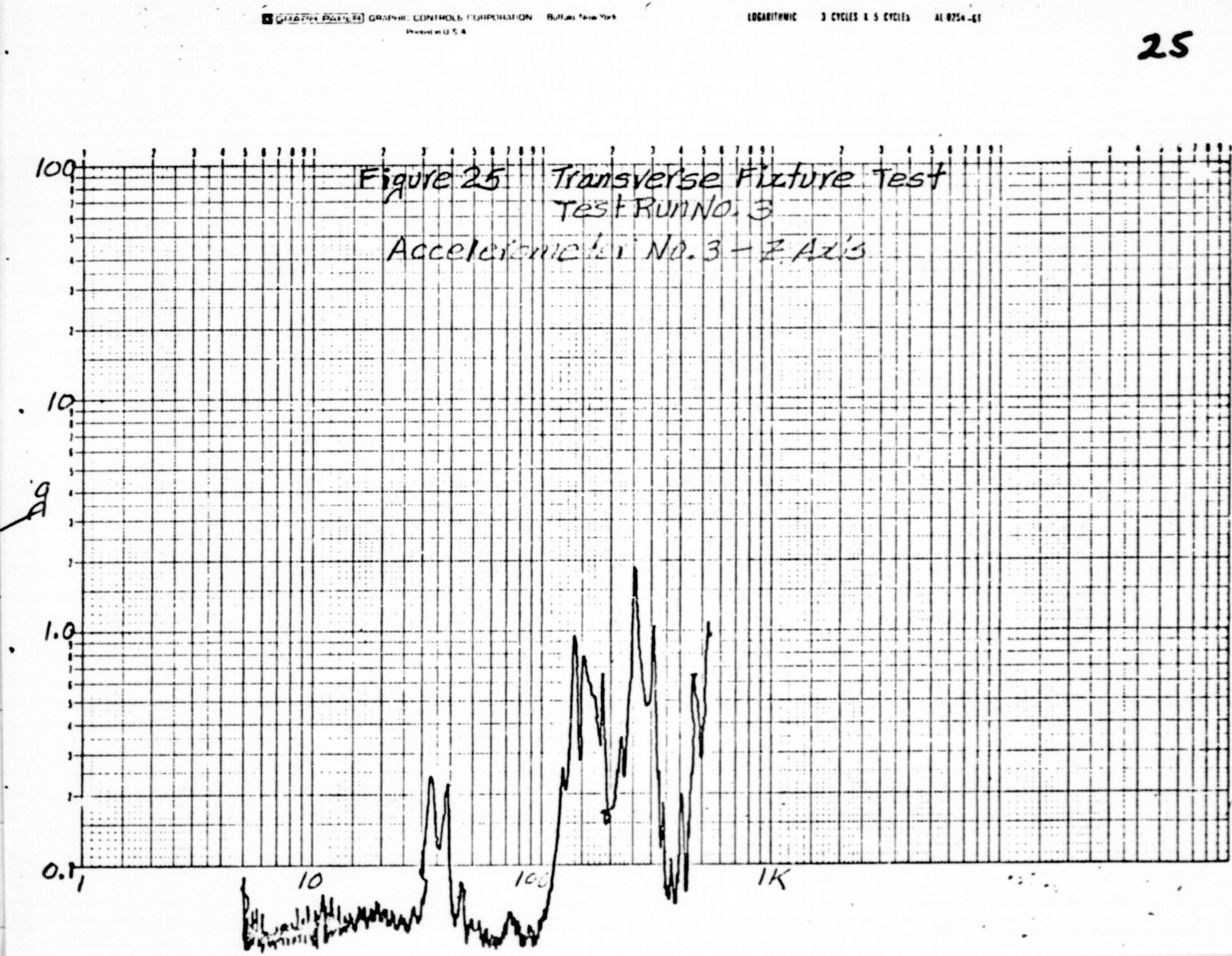


Figure 24 Transverse Fixture Test
Test Run No. 3
Accelerometer No. 2 - Control Accelerometer
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ
LOGARITHMIC 3 CYCLES X 5 CYCLES


GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
Printed in U.S.A.
LOGARITHMIC 3 CYCLES X 5 CYCLES AL 0254-61
Figure 25 Transverse Fixture Test
Test Run No. 3
Accelerometer No. 3 - Z Az's
100
10
1.0
0.1
g
1
10
100
1K

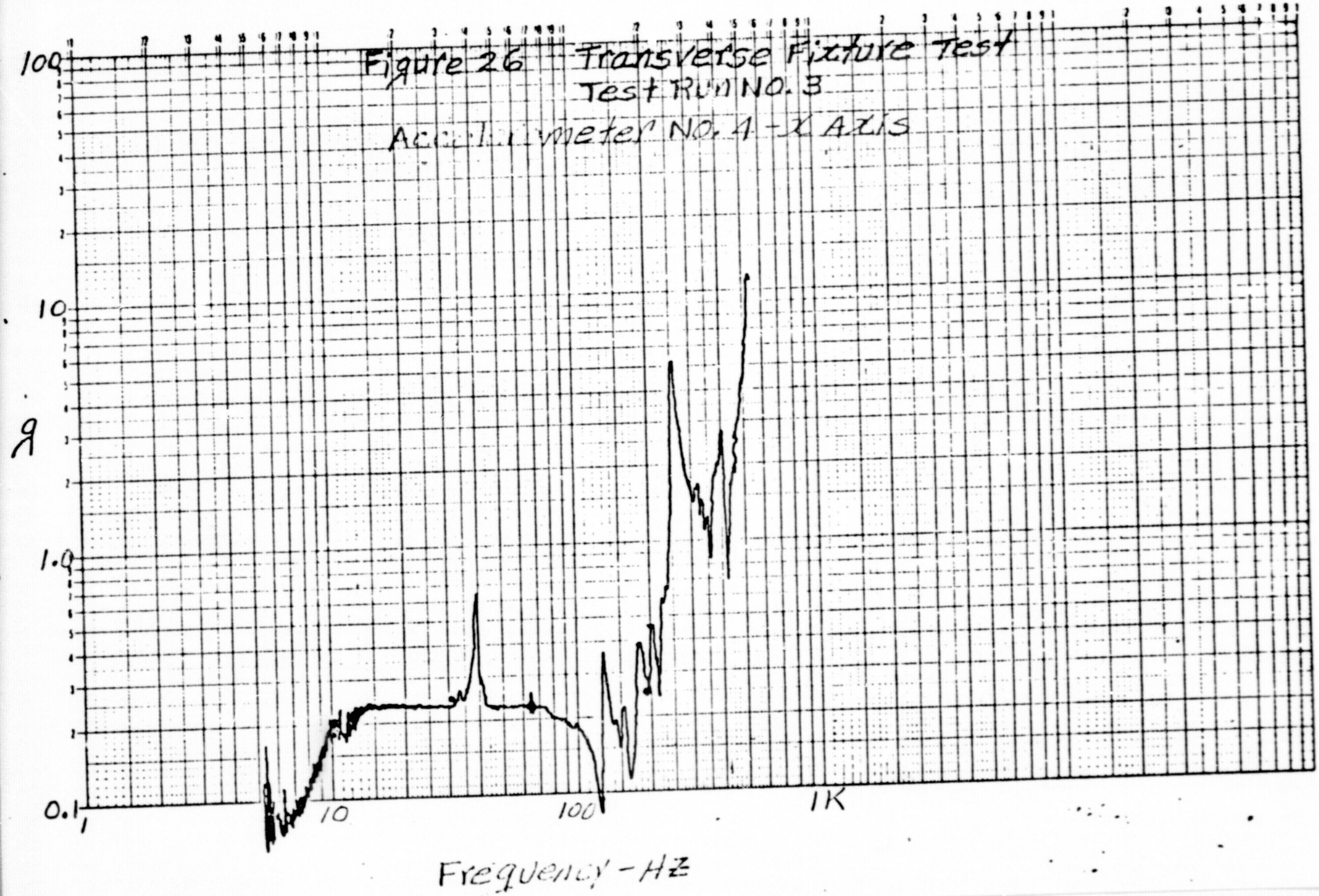


Figure 26 Transverse Fixture Test
Test Run NO. 3
Accelerometer NO. 1 - X AXIS

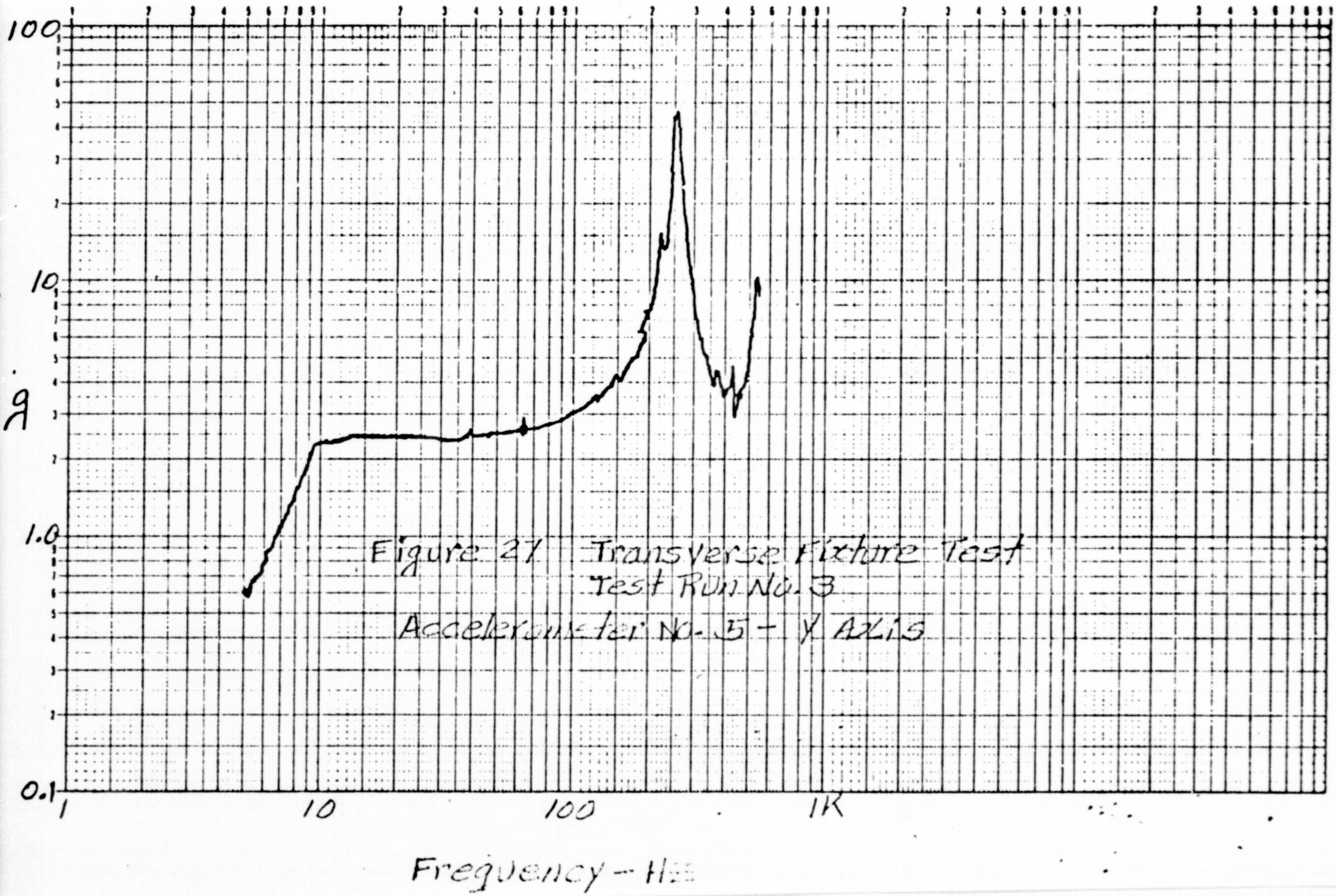
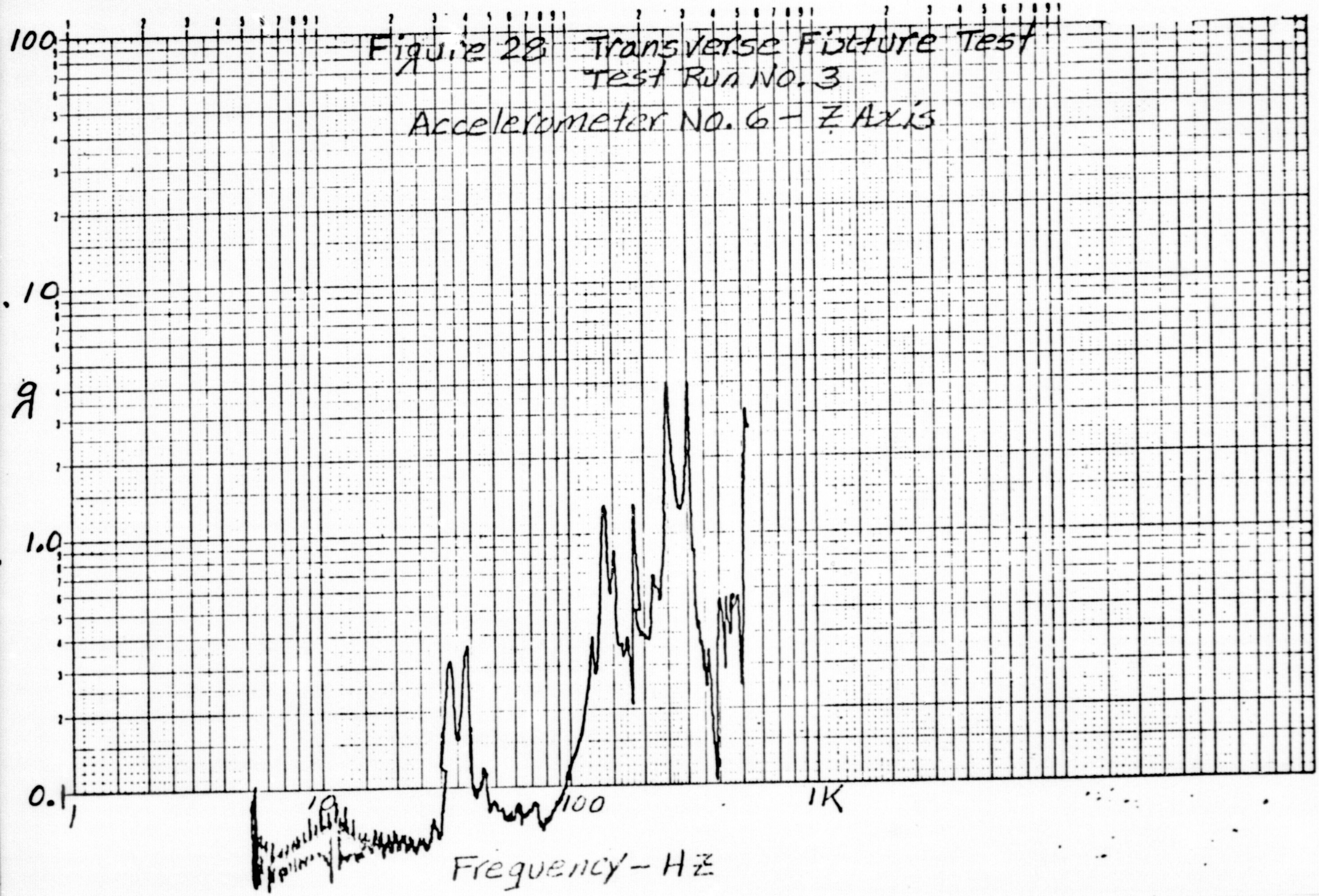
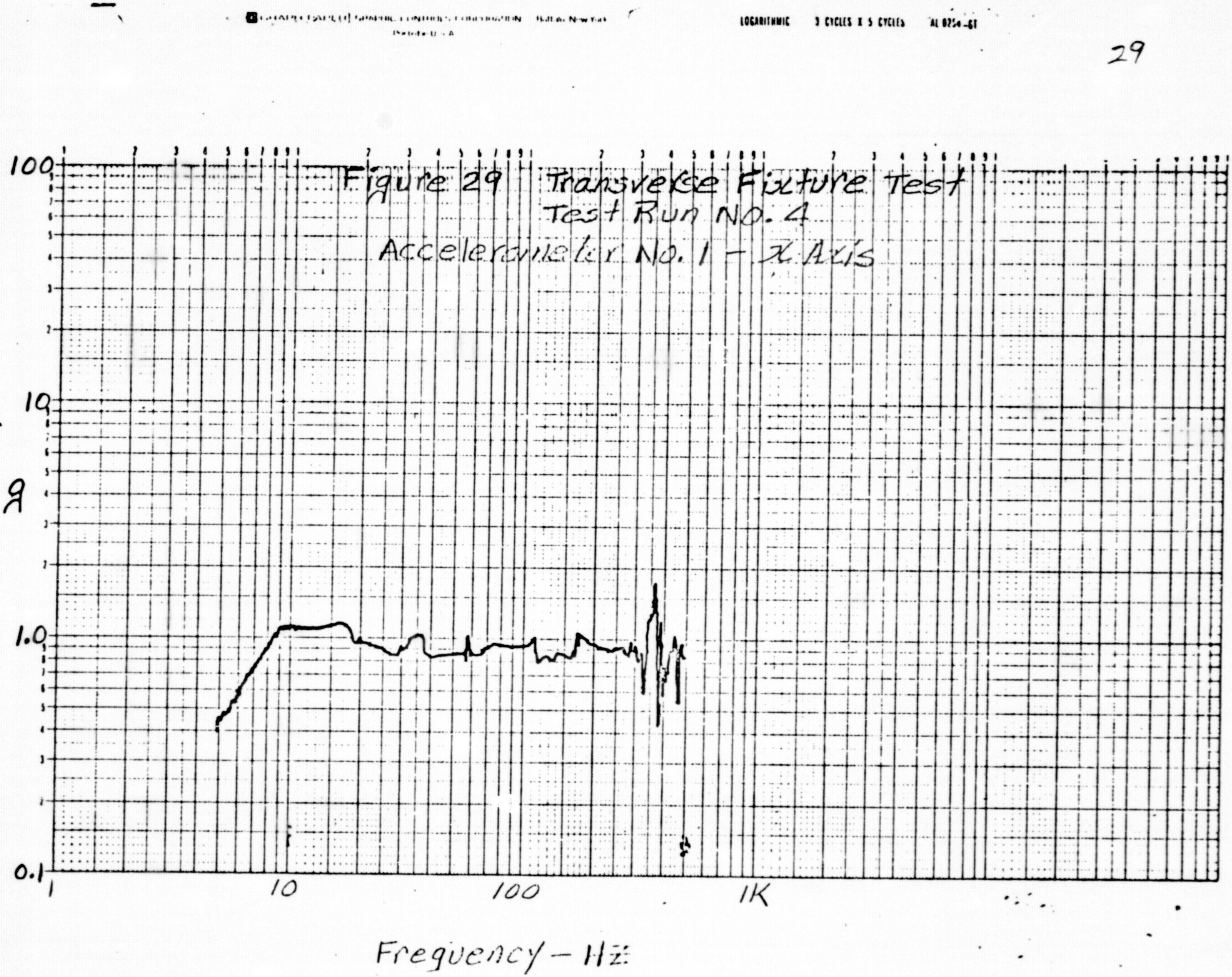


Figure 27 Transverse Fixture Test
Test Run No. 3
Accelerometer No. 5 - Y Axis

Figure 28 Transverse Fixture Test
Test Run No. 3
Accelerometer No. 6 – Z Axis




LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 29 Transverse Fixture Test
Test Run NO. 4
Accelerometer No. 1 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - Hz

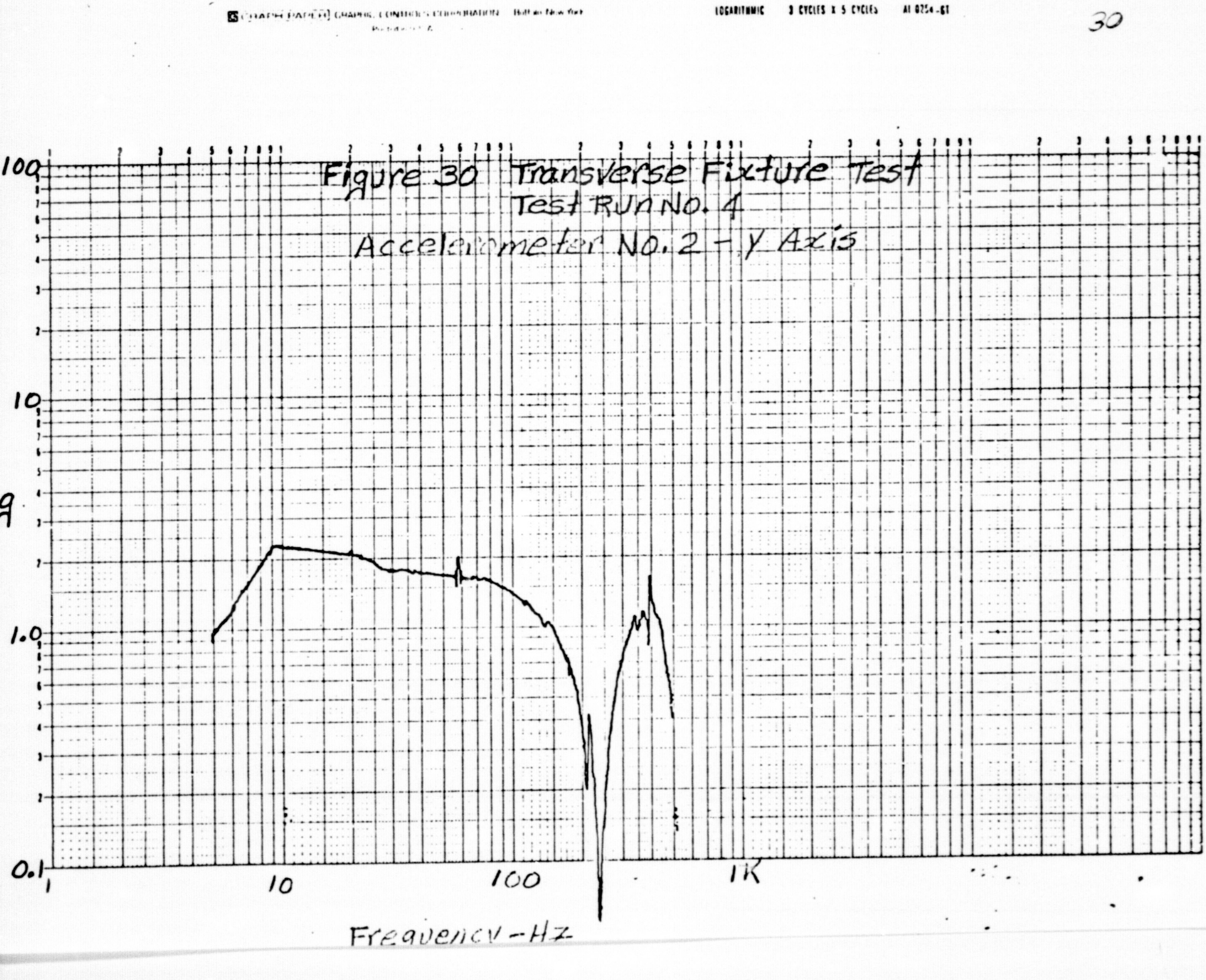


Figure 30 Transverse Fixture Test
Test Run No. 4
Accelerometer No. 2 - Y Axis

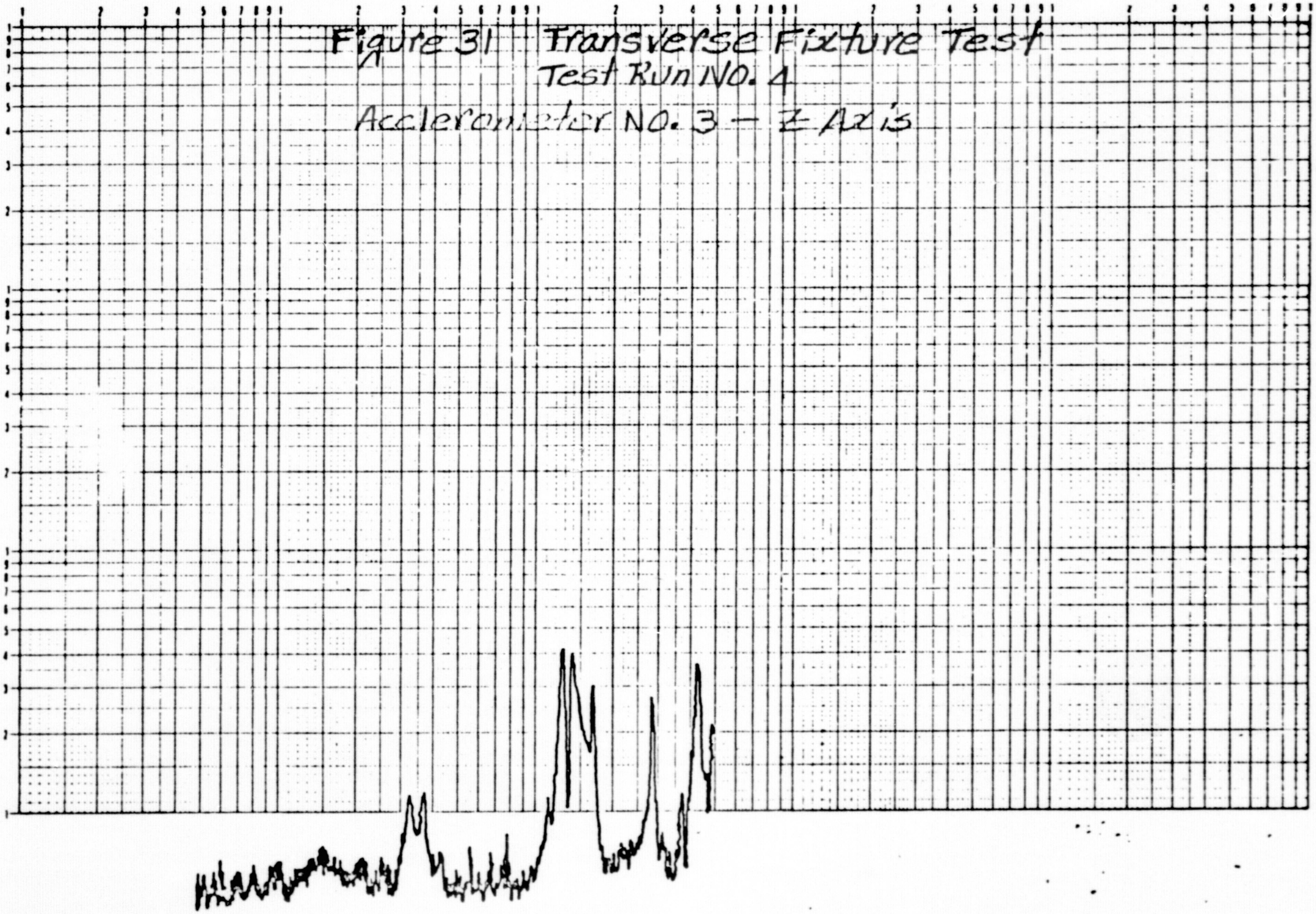
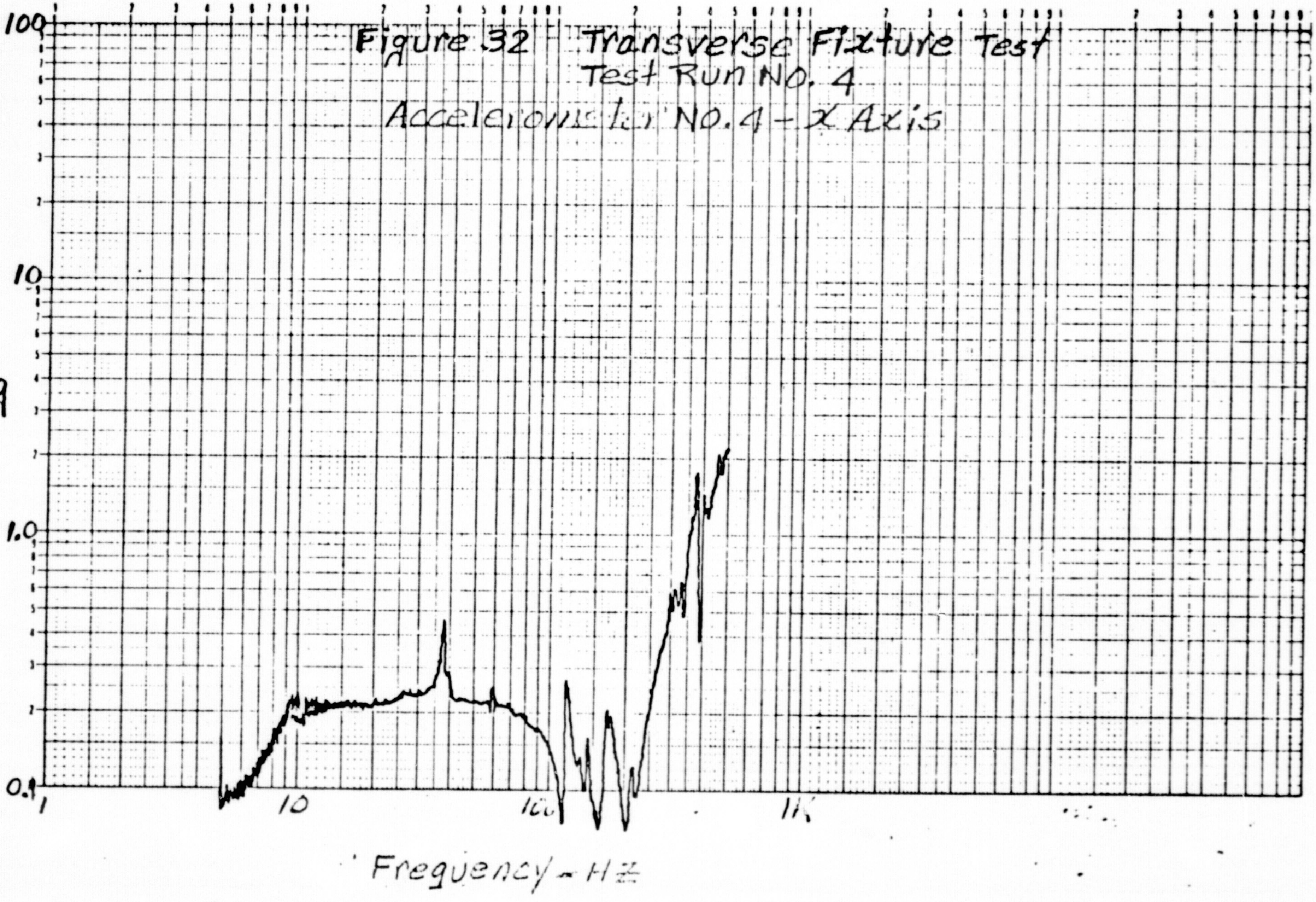
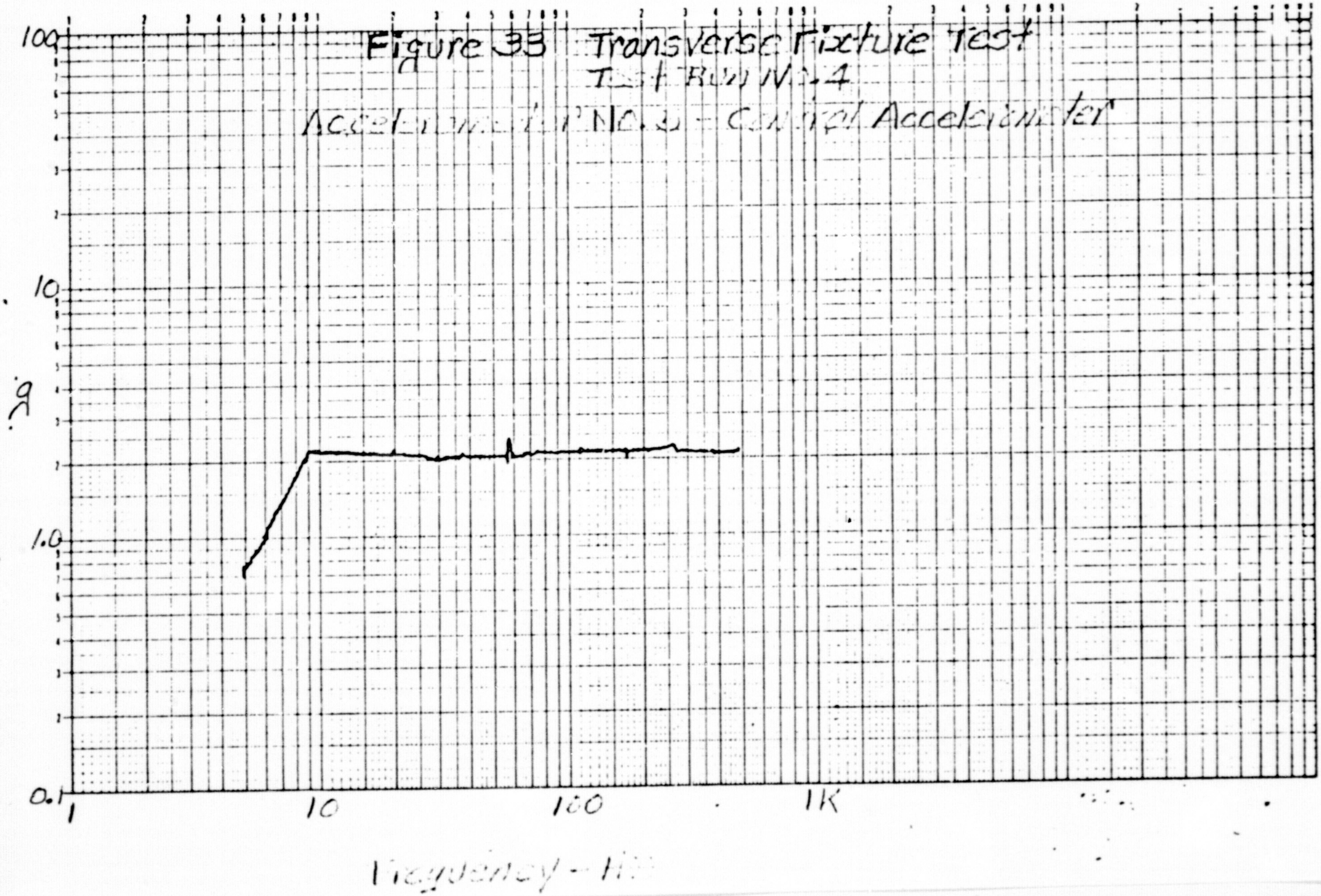
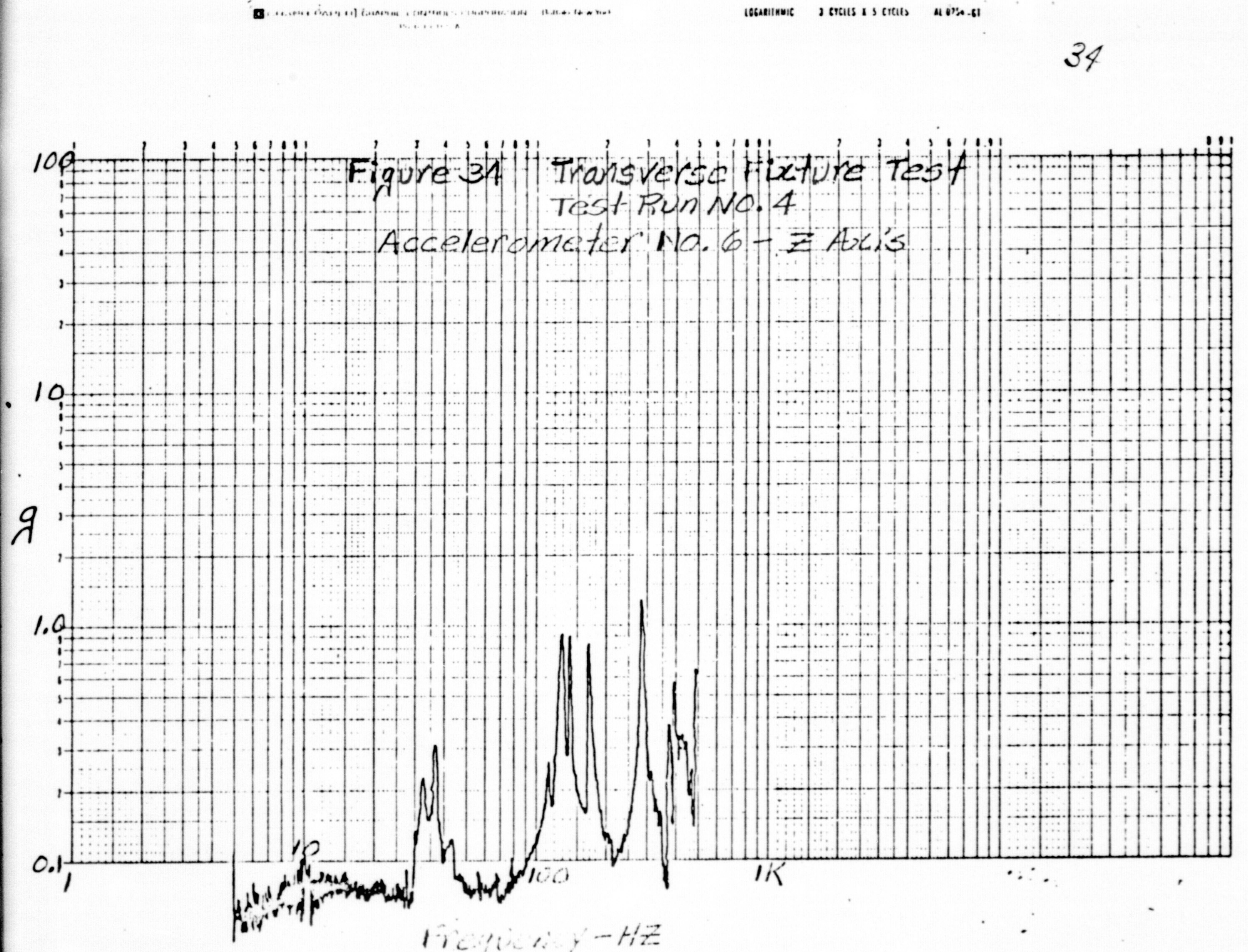


Figure 31 Transverse Fixture Test
Test Run NO. 4
Accleromater NO. 3 – Z Axis

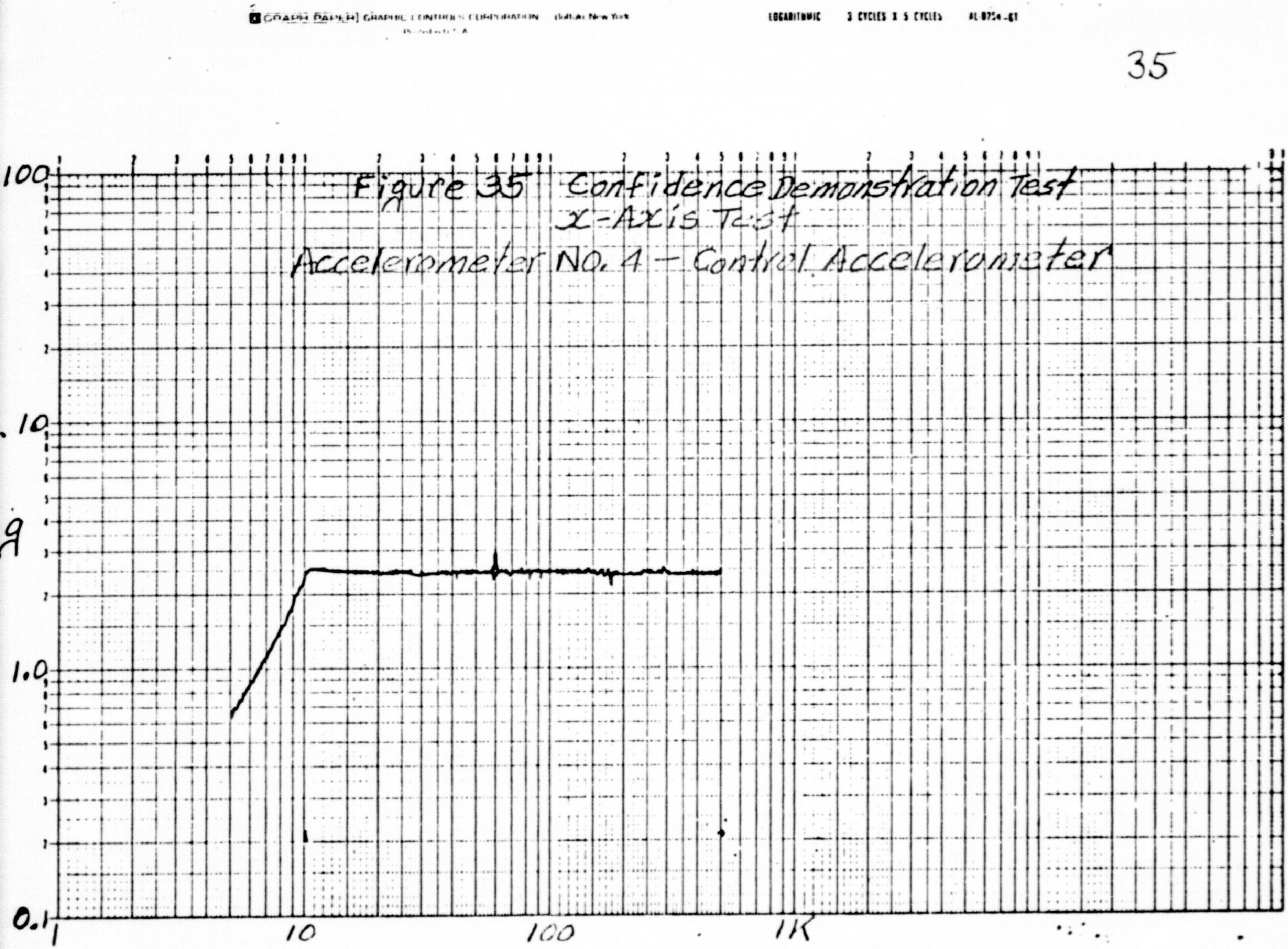
Figure 32 Transverse Fixture Test
Test Run No. 4
Accelerometer No. 4 - X Axis




LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 33 Transverse Fixture Test
Test Run No. 4
Accelerometer No. 2 - Control Accelerometer
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz



LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 34 Transverse Fixture Test
Test Run No. 4
Accelerometer No. 6 - Z Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ


GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 35 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 4 - Control Accelerometer
100
10
g
1.0
0.1
1
10
100
1K

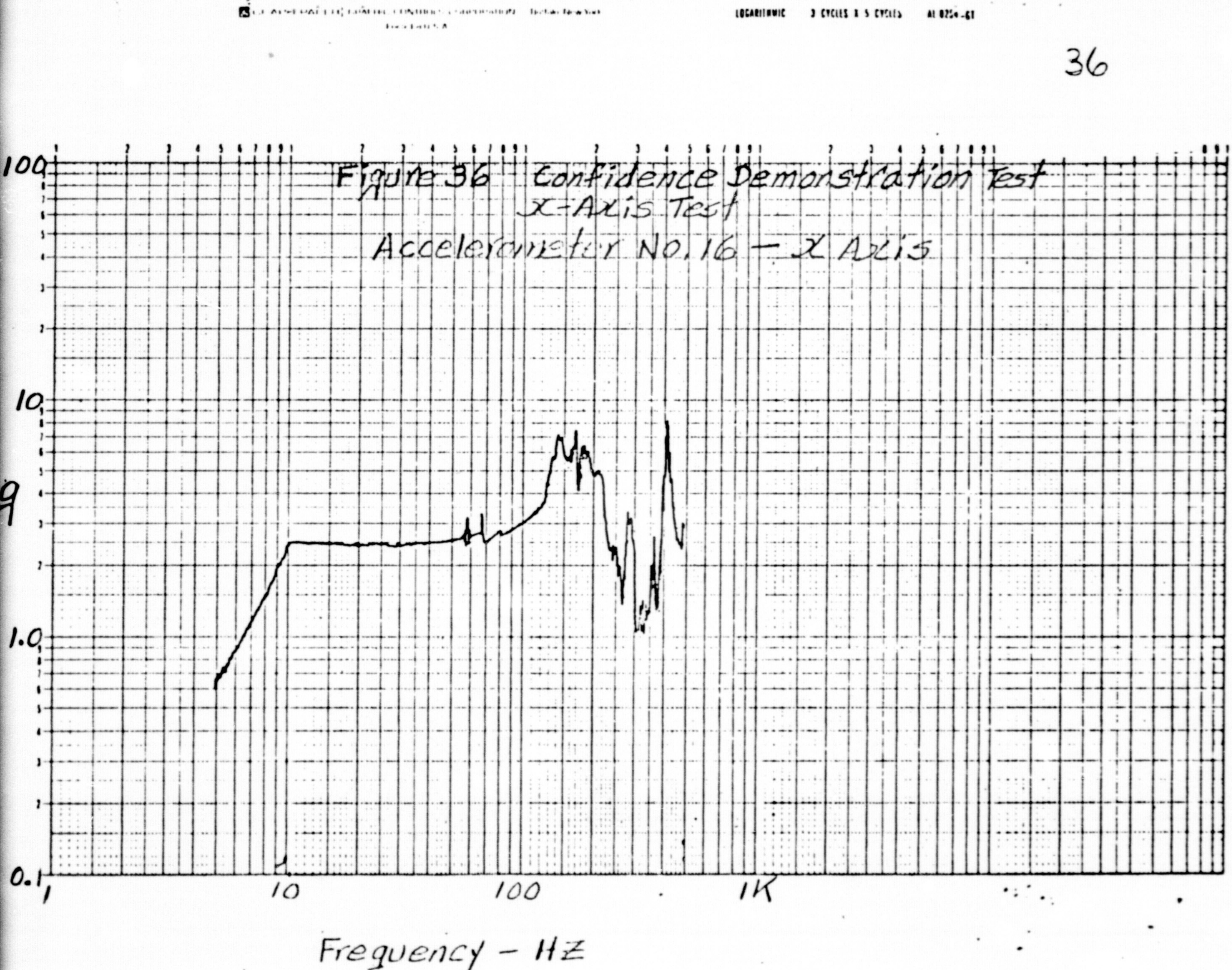
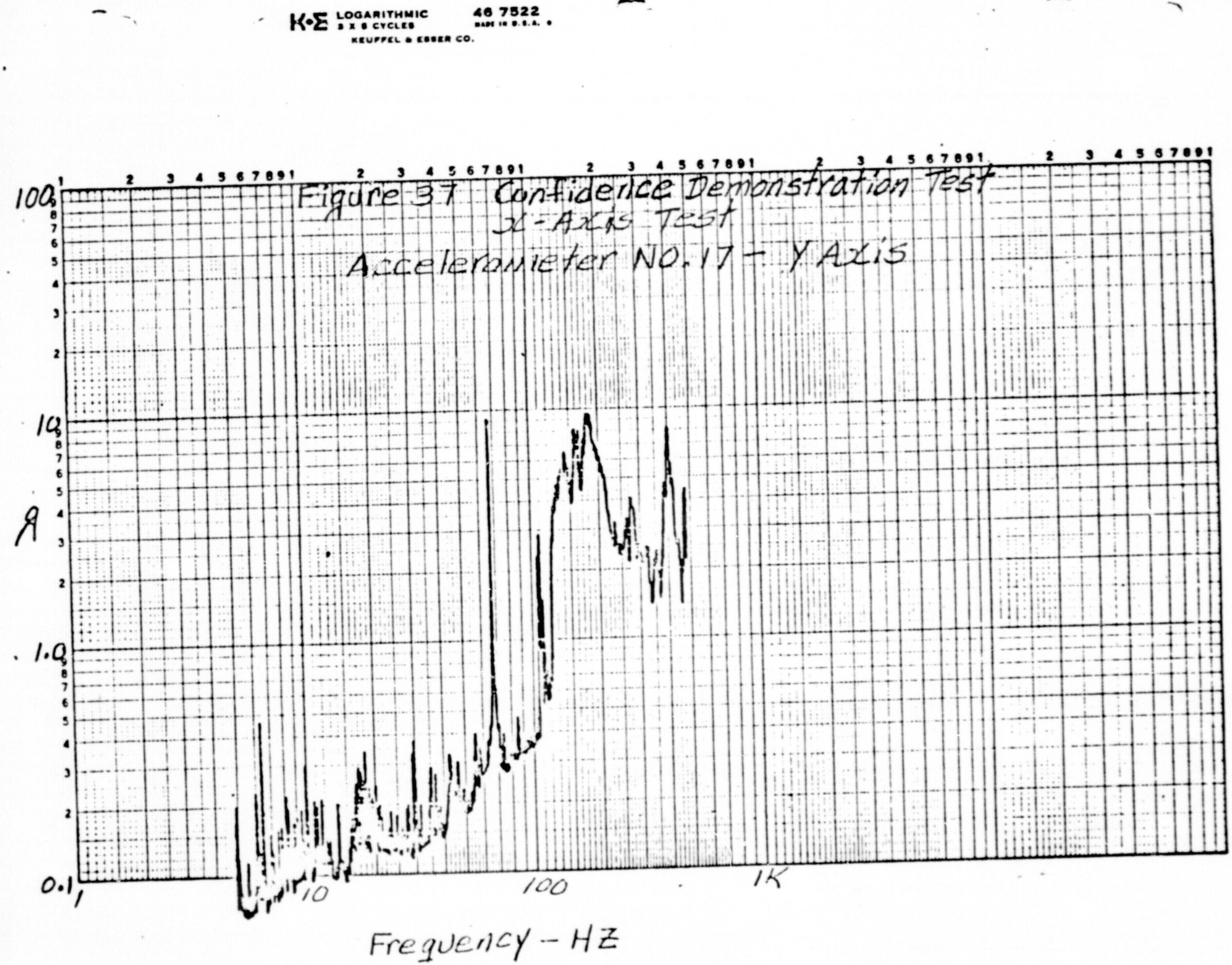


Figure 36 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 16 - X Axis


K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO.
46 7522 MADE IN U.S.A.
Figure 37 Confidence Demonstration Test
X-Axis Test
Accelerometer NO. 17 - Y AXIS
100
10
1.0
0.1
A
1
10
100
1K
Frequency - HZ

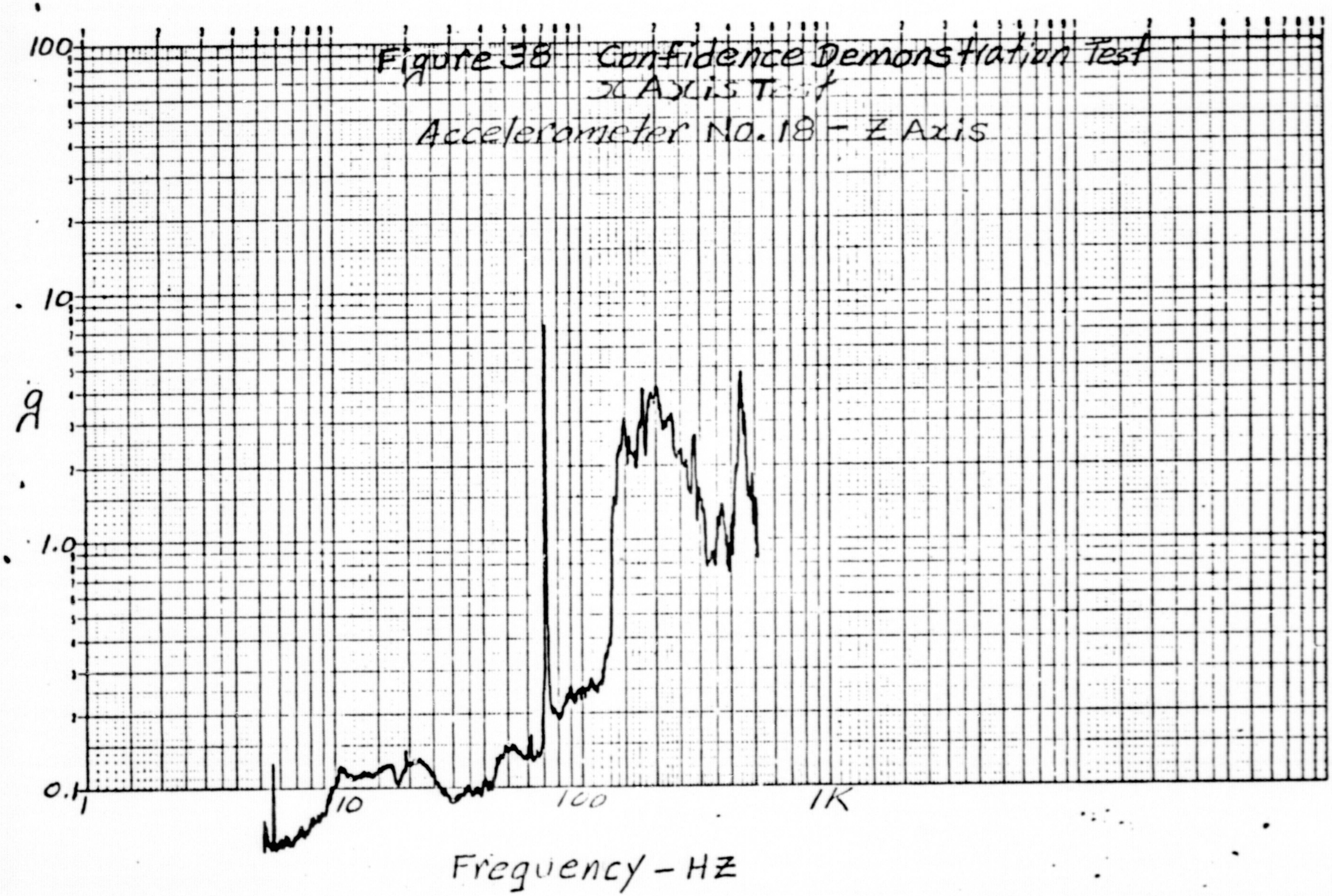
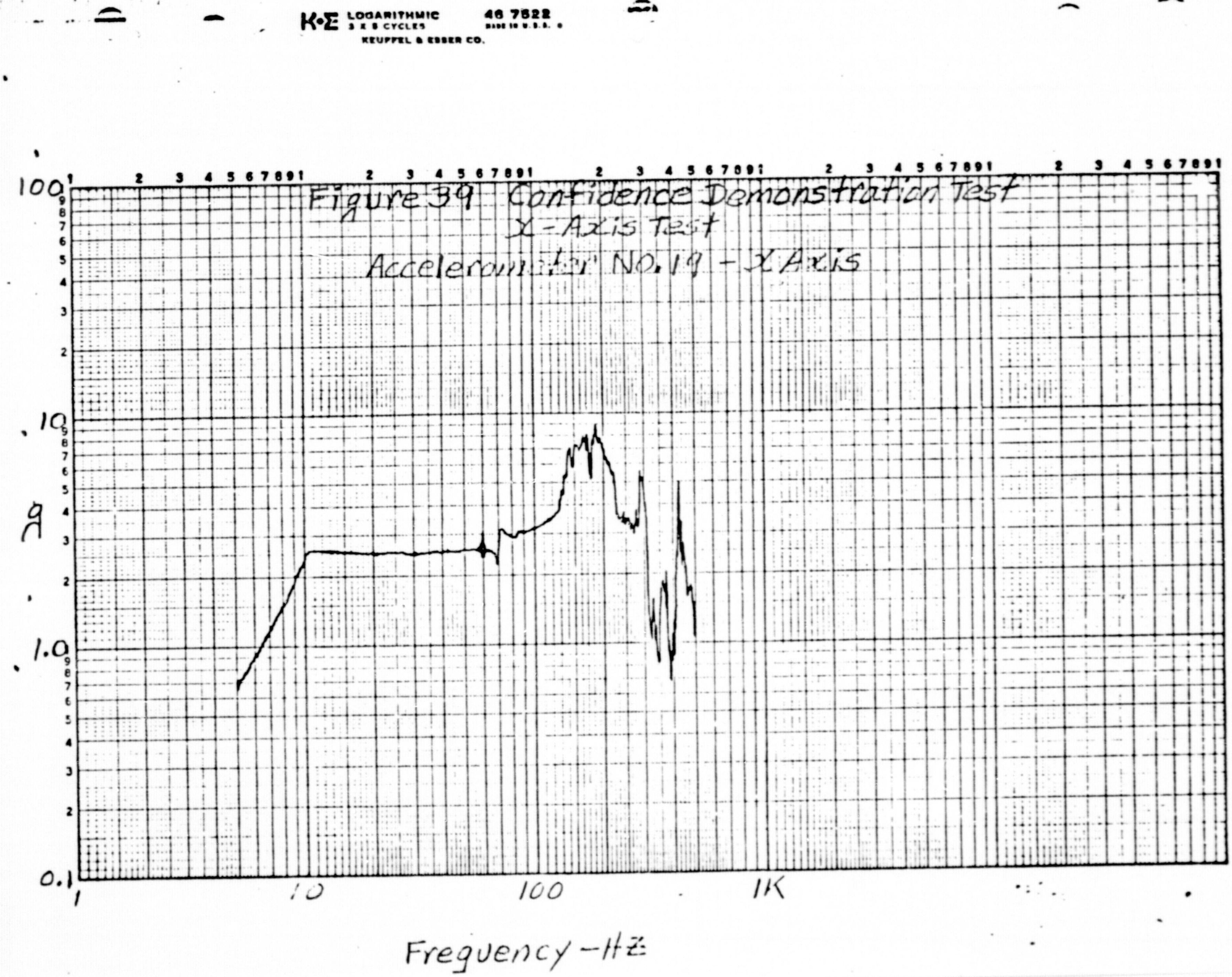
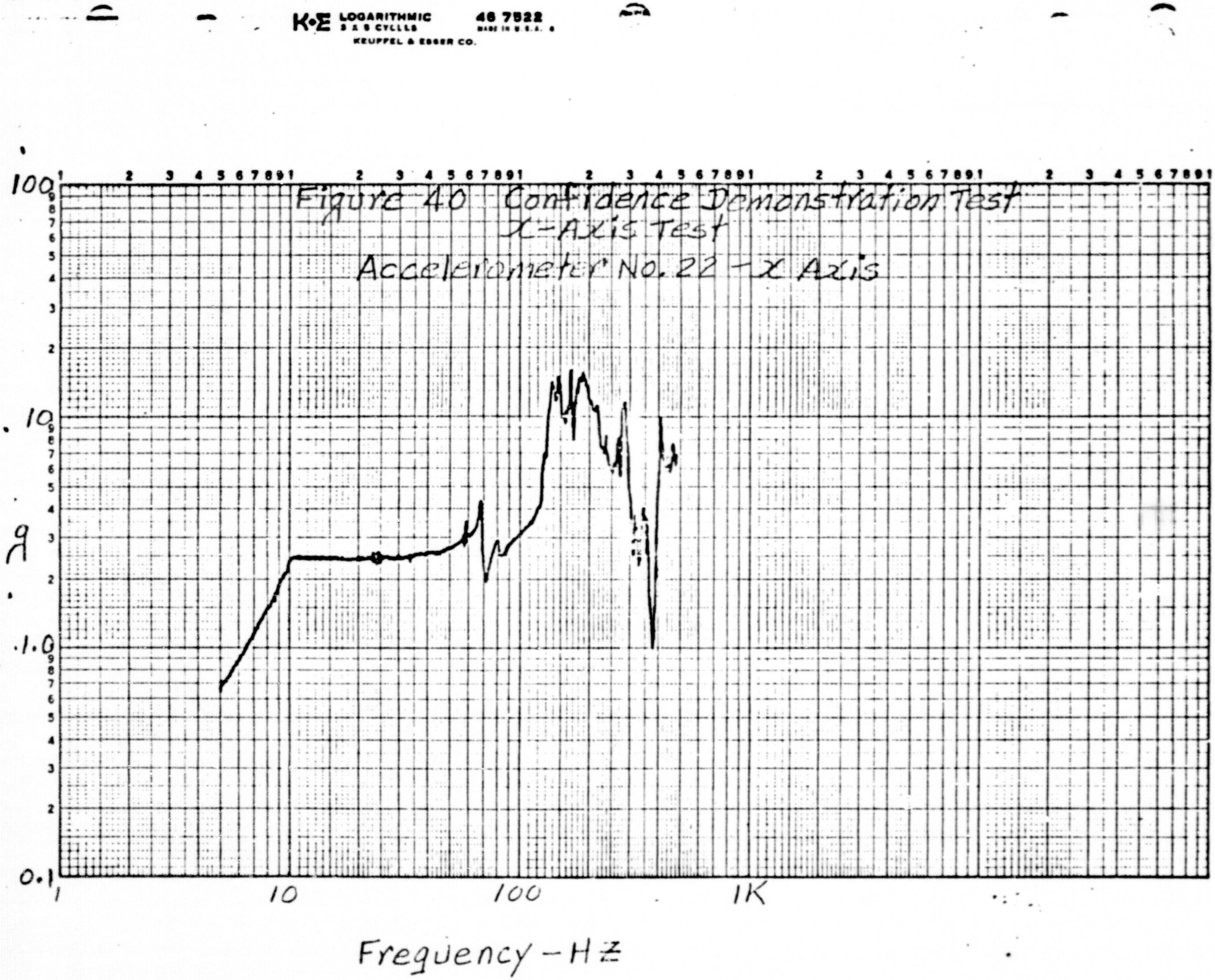


Figure 38 Confidence Demonstration Test
X Axis Test
Accelerometer No. 18 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ


K·E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522
Figure 39 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 19 - X Axis
g
100
10
1.0
0.1
1
10
100
1K
Frequency - Hz


K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO.
46 7522 MADE IN U.S.A.
Figure 40 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 22 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - Hz

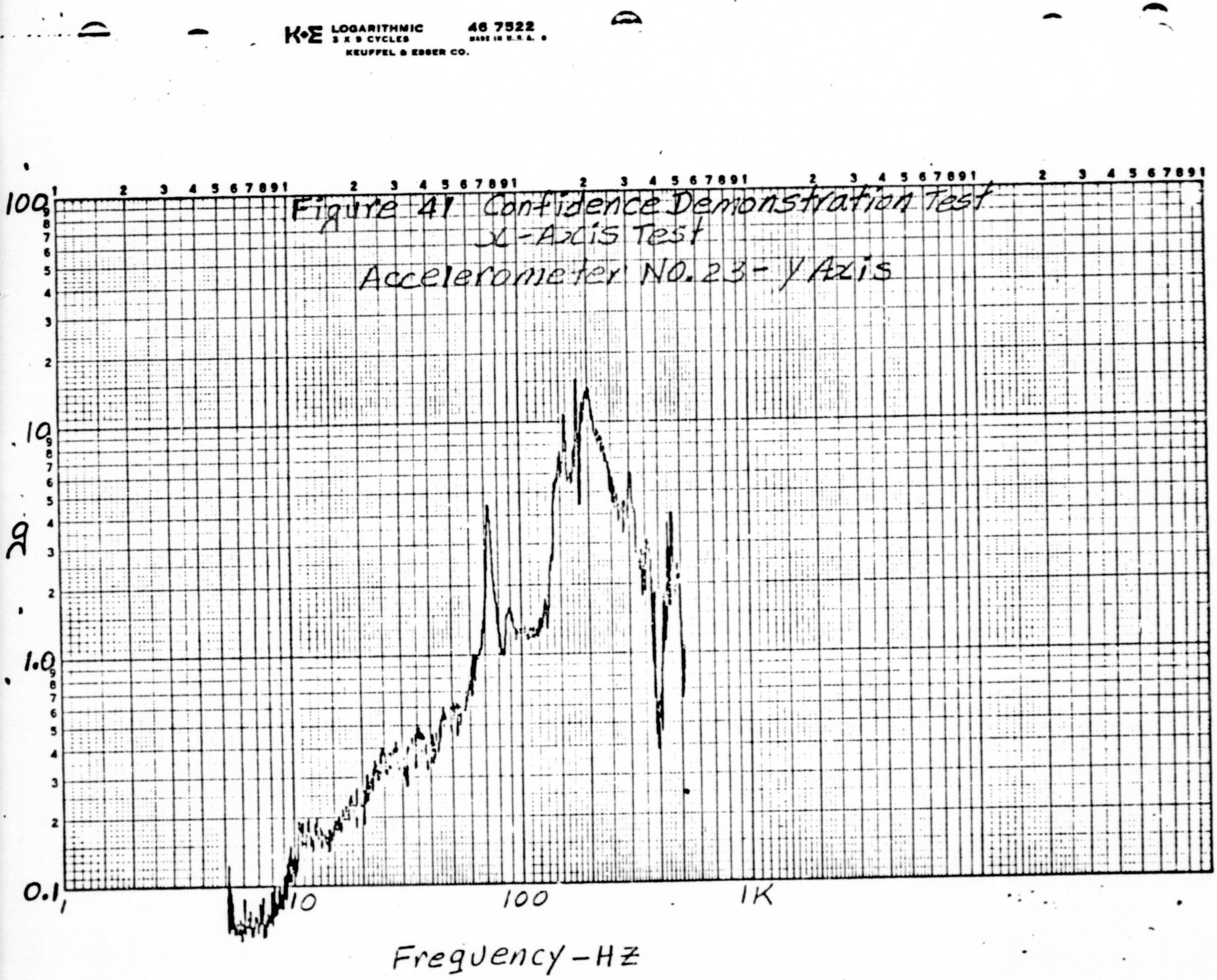
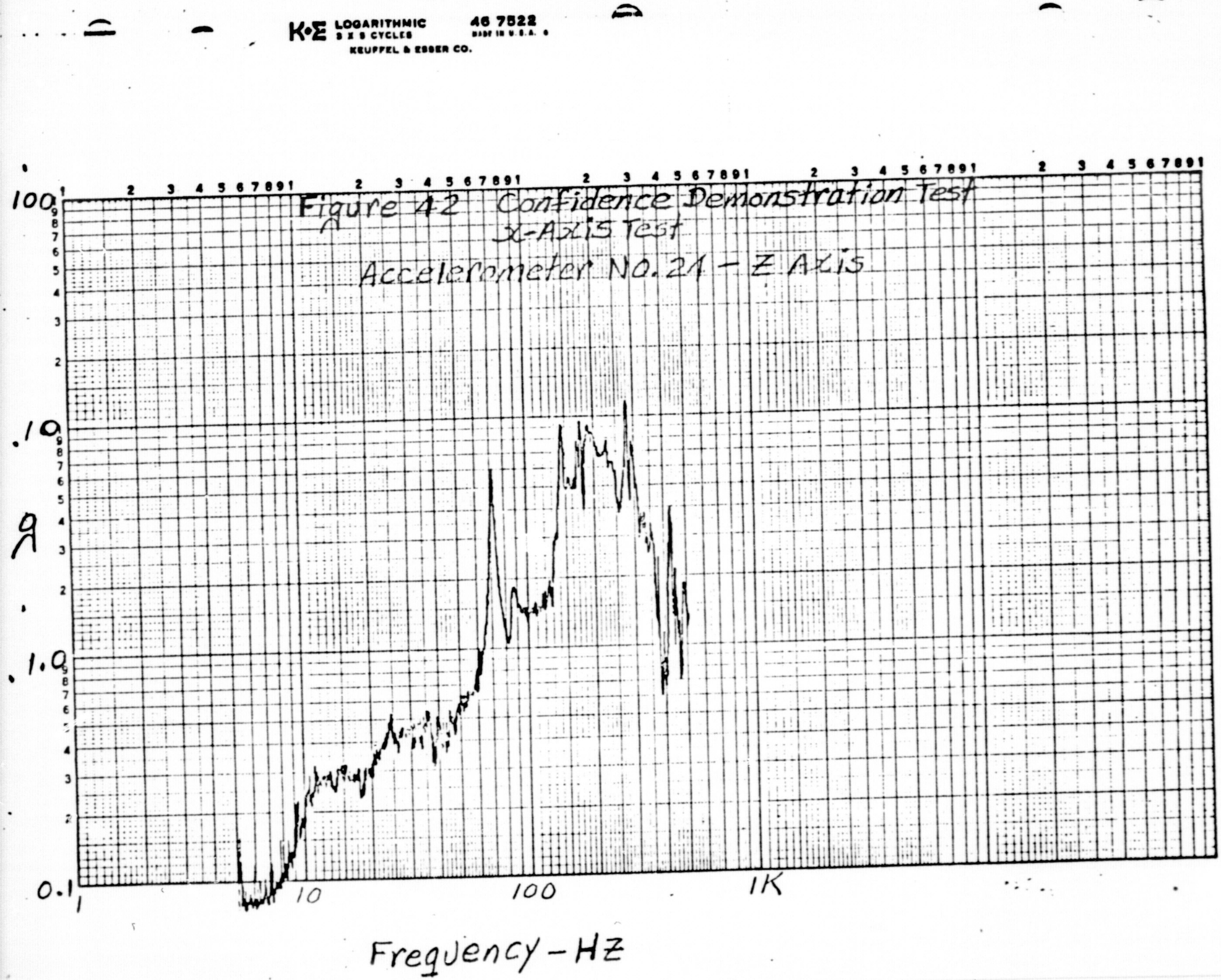


Figure 41 Confidence Demonstration Test
X-Axis Test
Accelerometer NO. 23 - Y Axis


K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO.
46 7522 MADE IN U.S.A.
Figure 42 Confidence Demonstration Test
X-AXIS Test
Accelerometer NO. 21 - Z AXIS
100
.10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

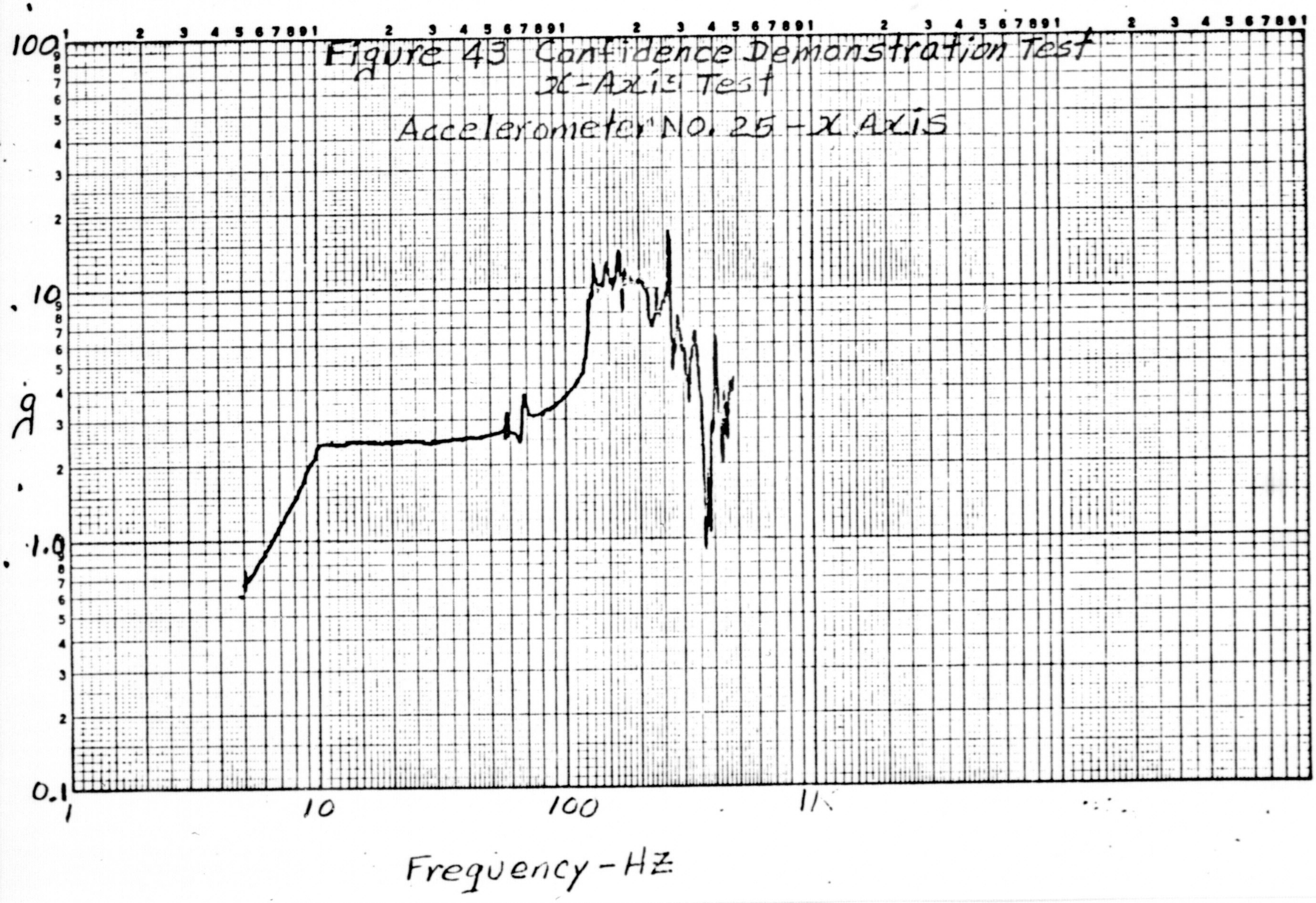


Figure 43 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 25 - X Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency-HZ

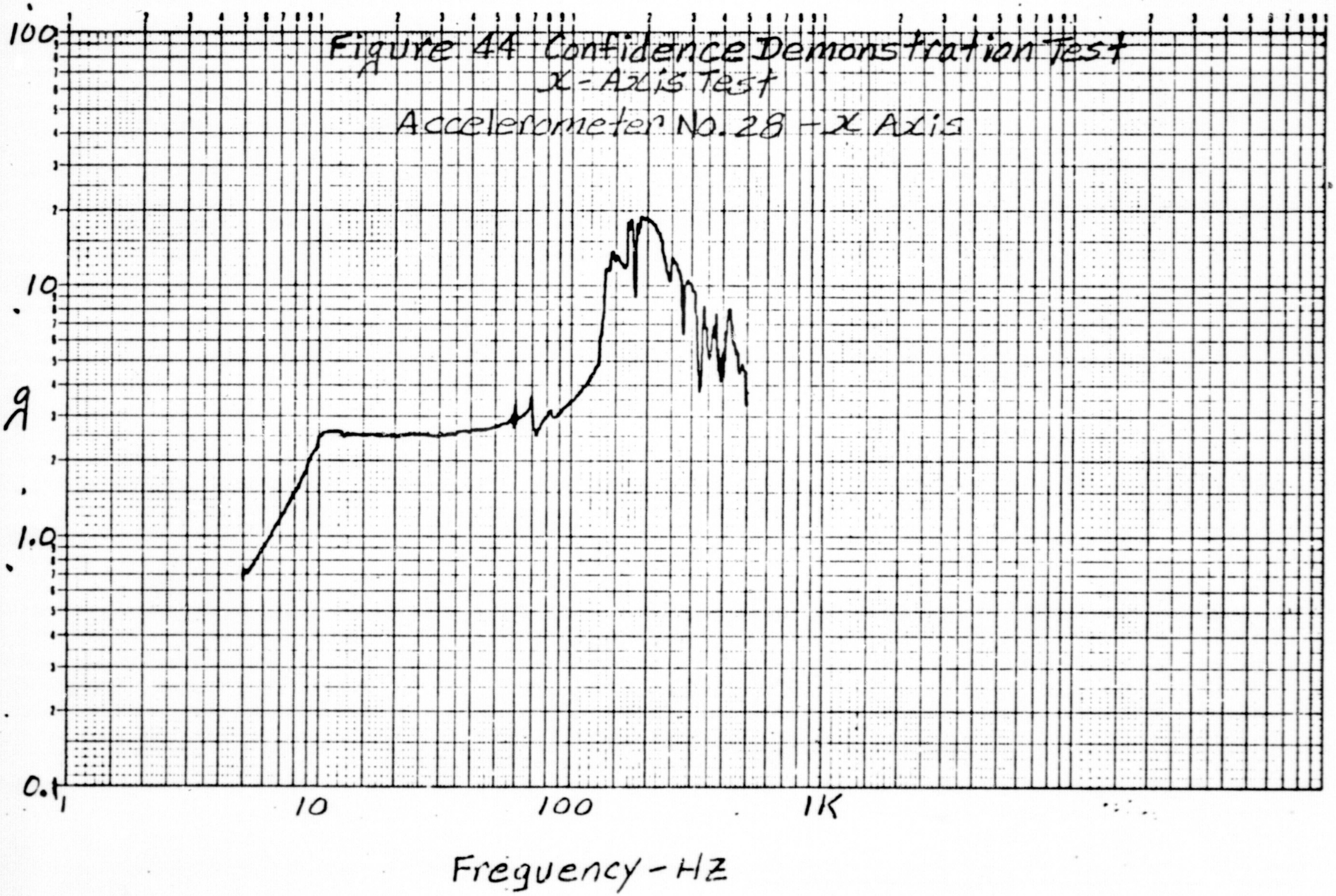


Figure 44 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 28 - X Axis

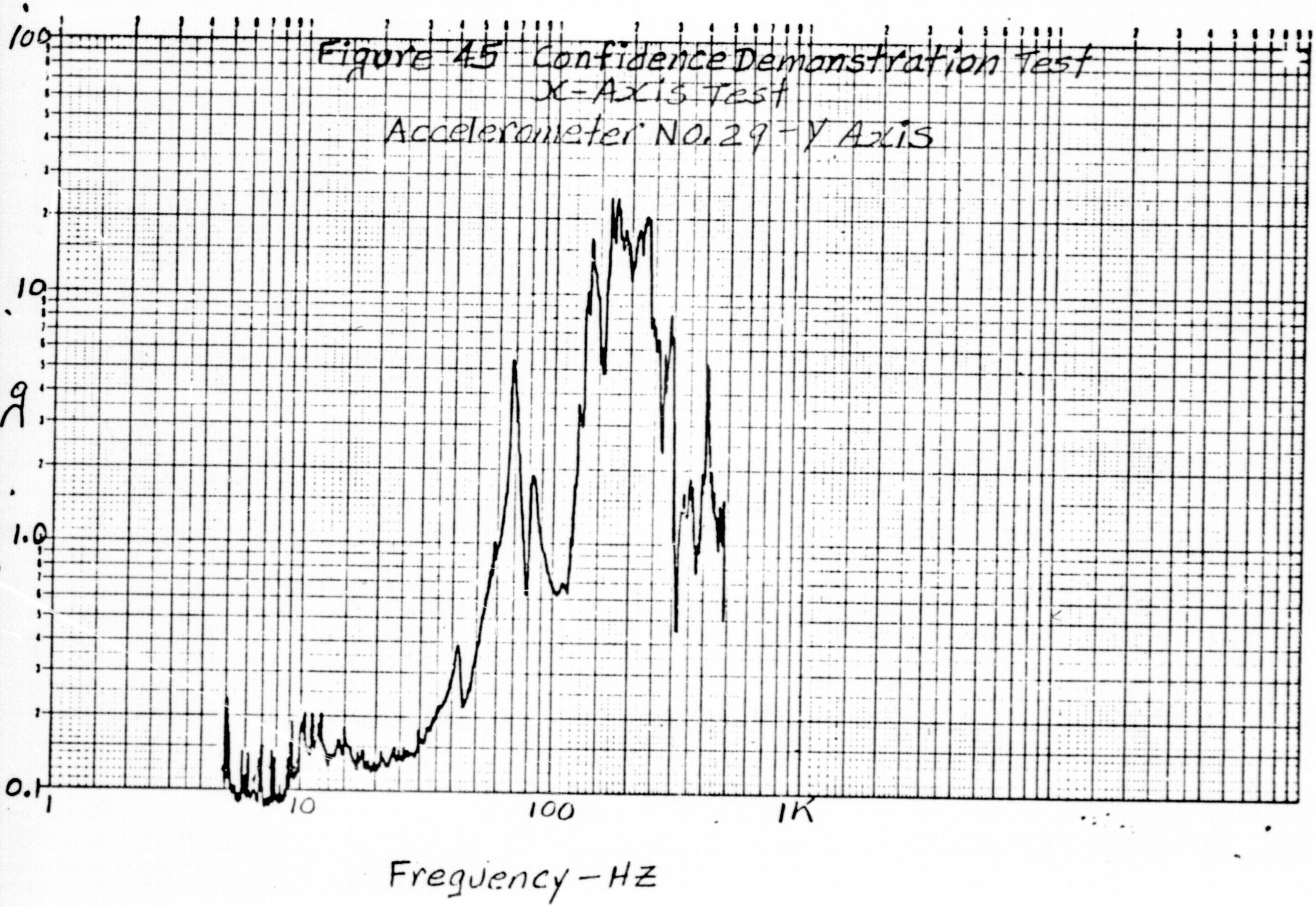


Figure 45 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 29 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

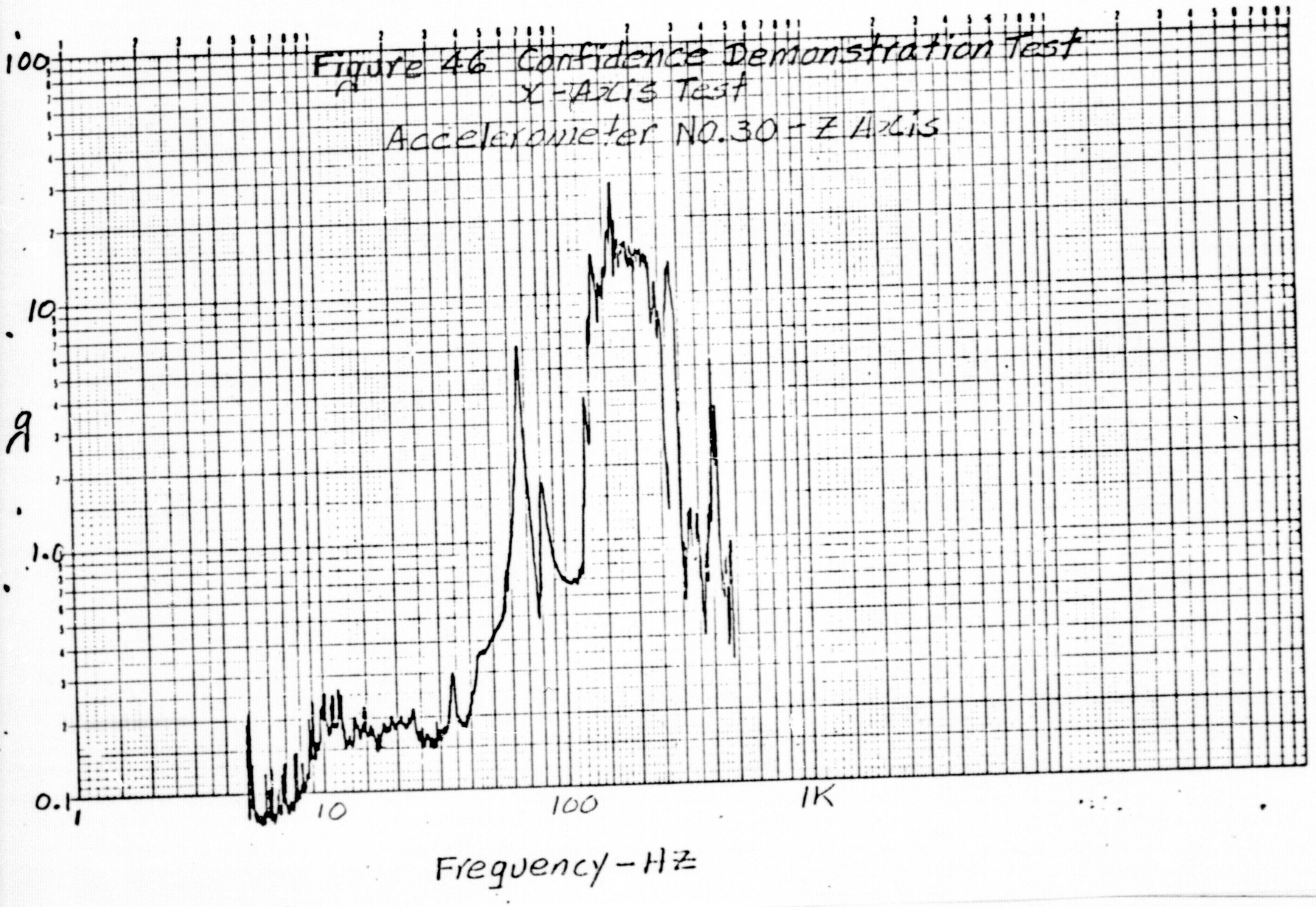


Figure 46 Confidence Demonstration Test
X-Axis Test
Accelerometer NO.30 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

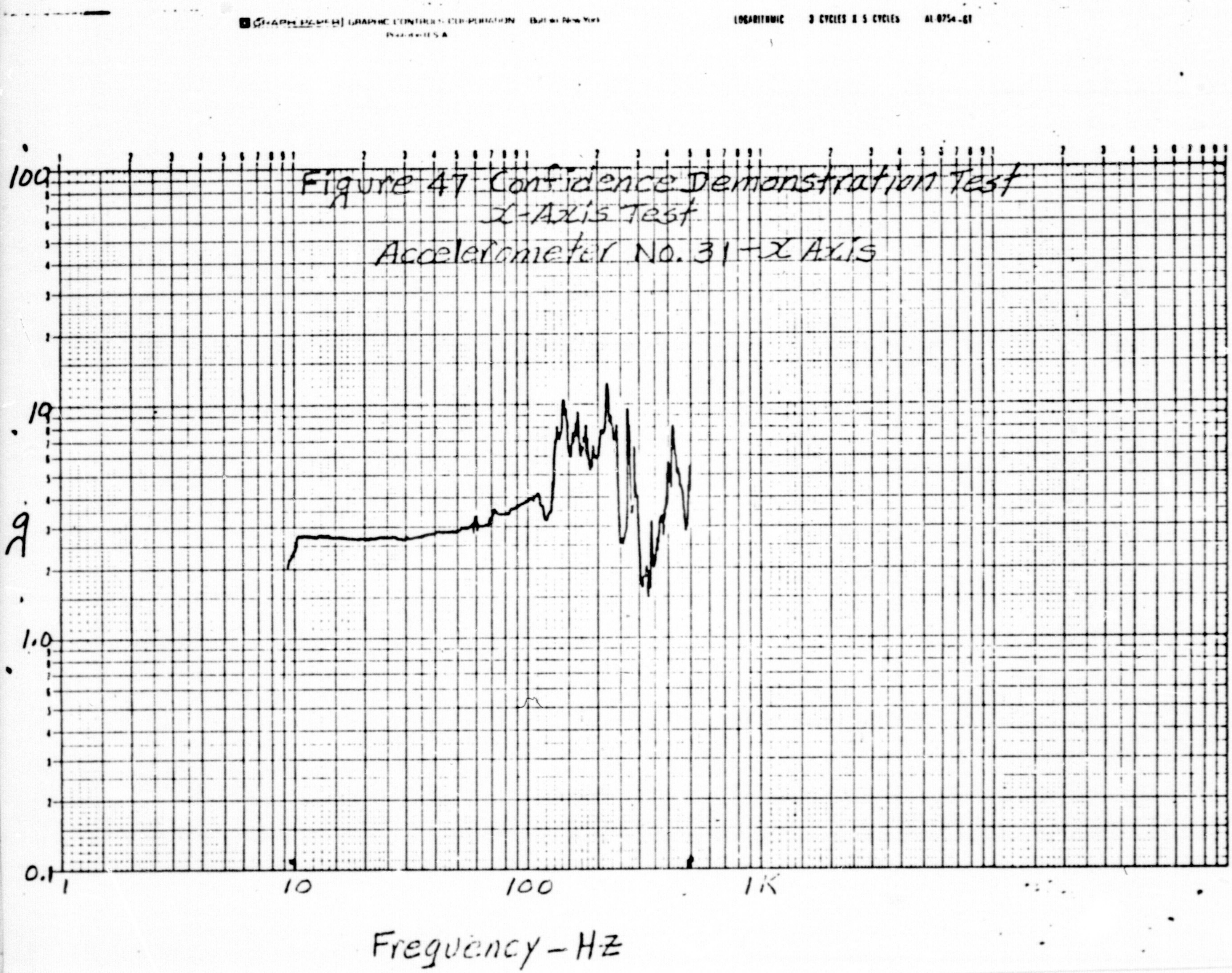
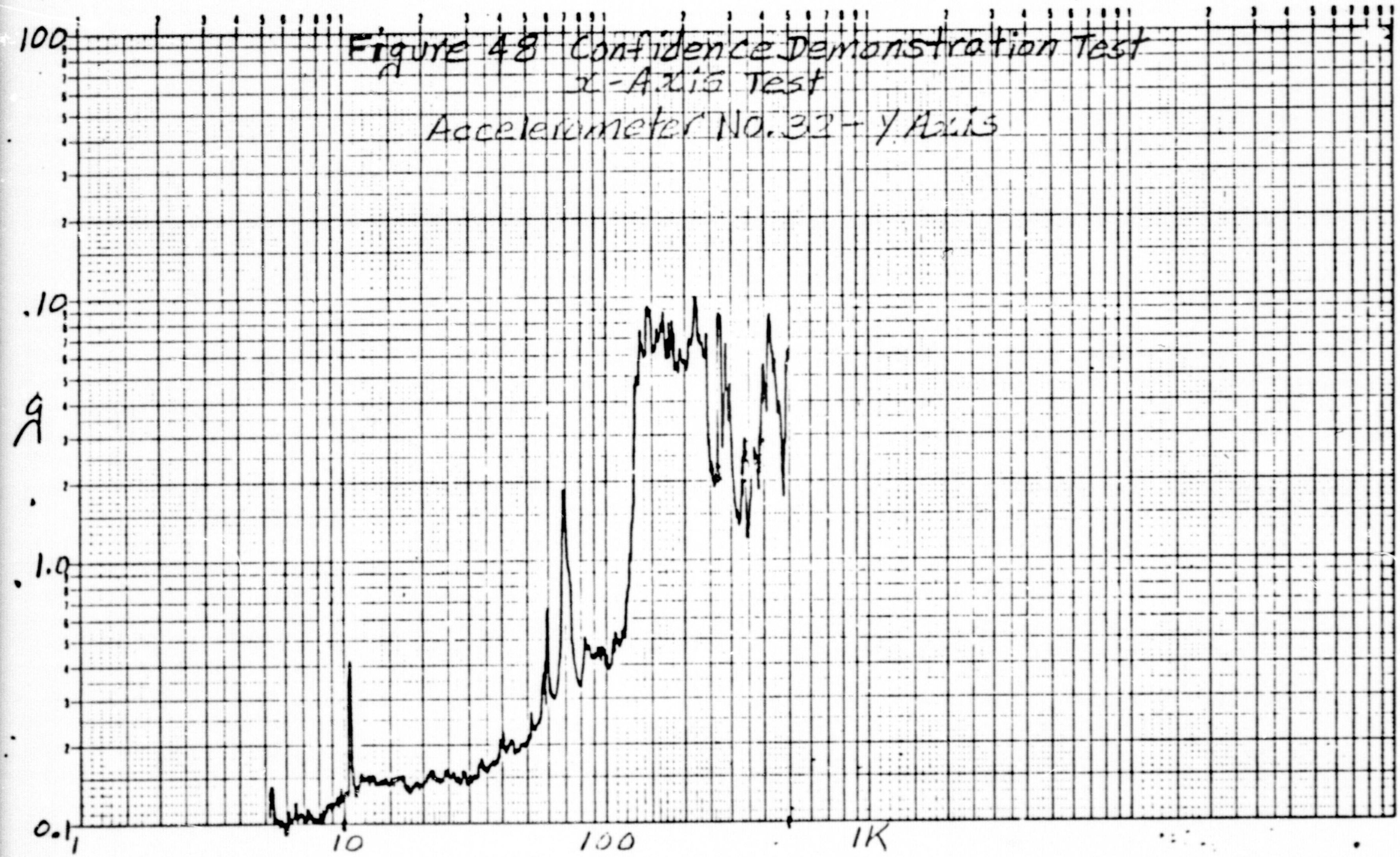

GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo New York Printed in U.S.A.
LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 47 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 31 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - Hz

Figure 48 Confidence Demonstration Test
x-Axis Test
Accelerometer No. 33 - Y Axis



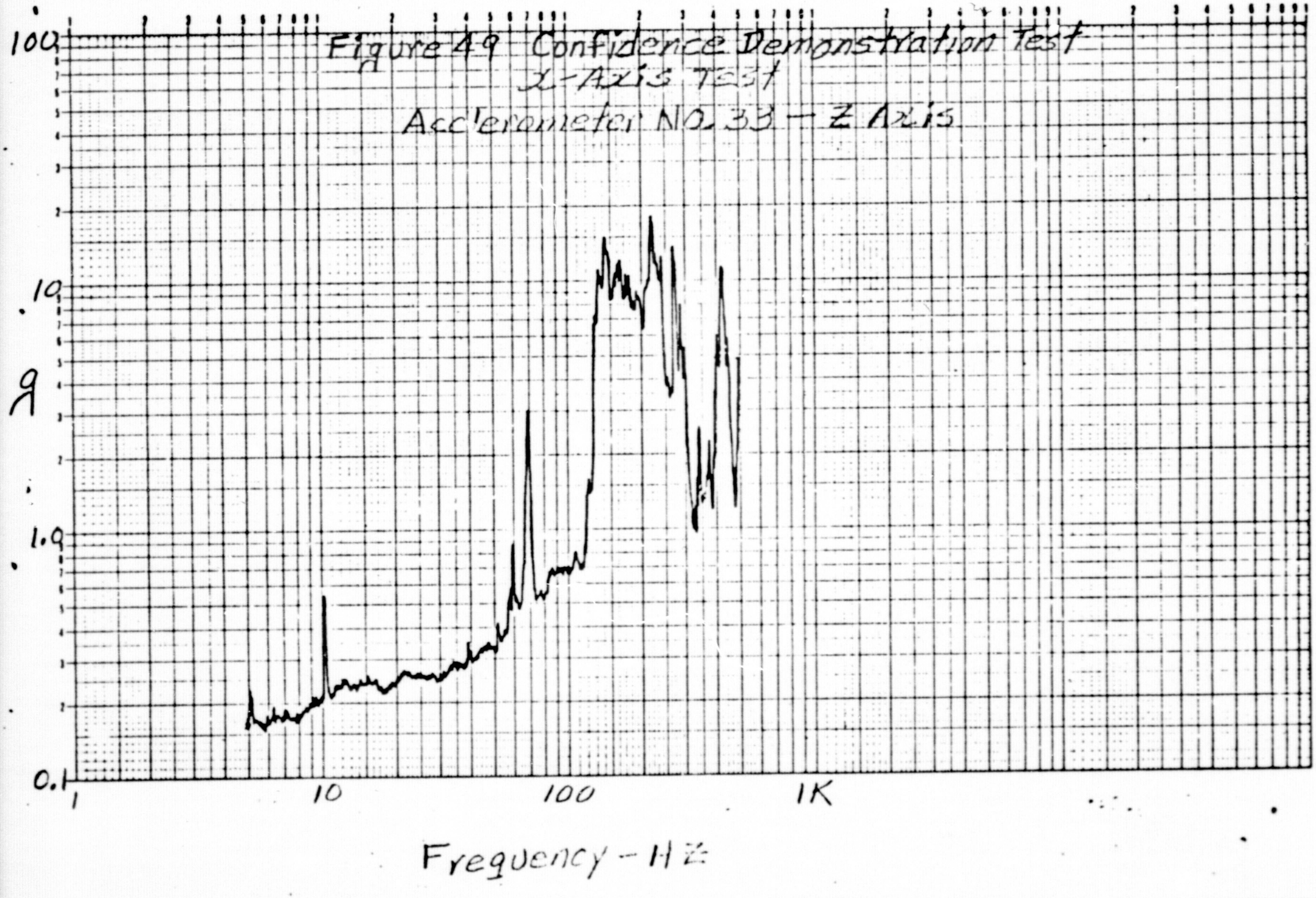


Figure 49 Confidence Demonstration Test
Z-Axis Test
Accelerometer NO. 33 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

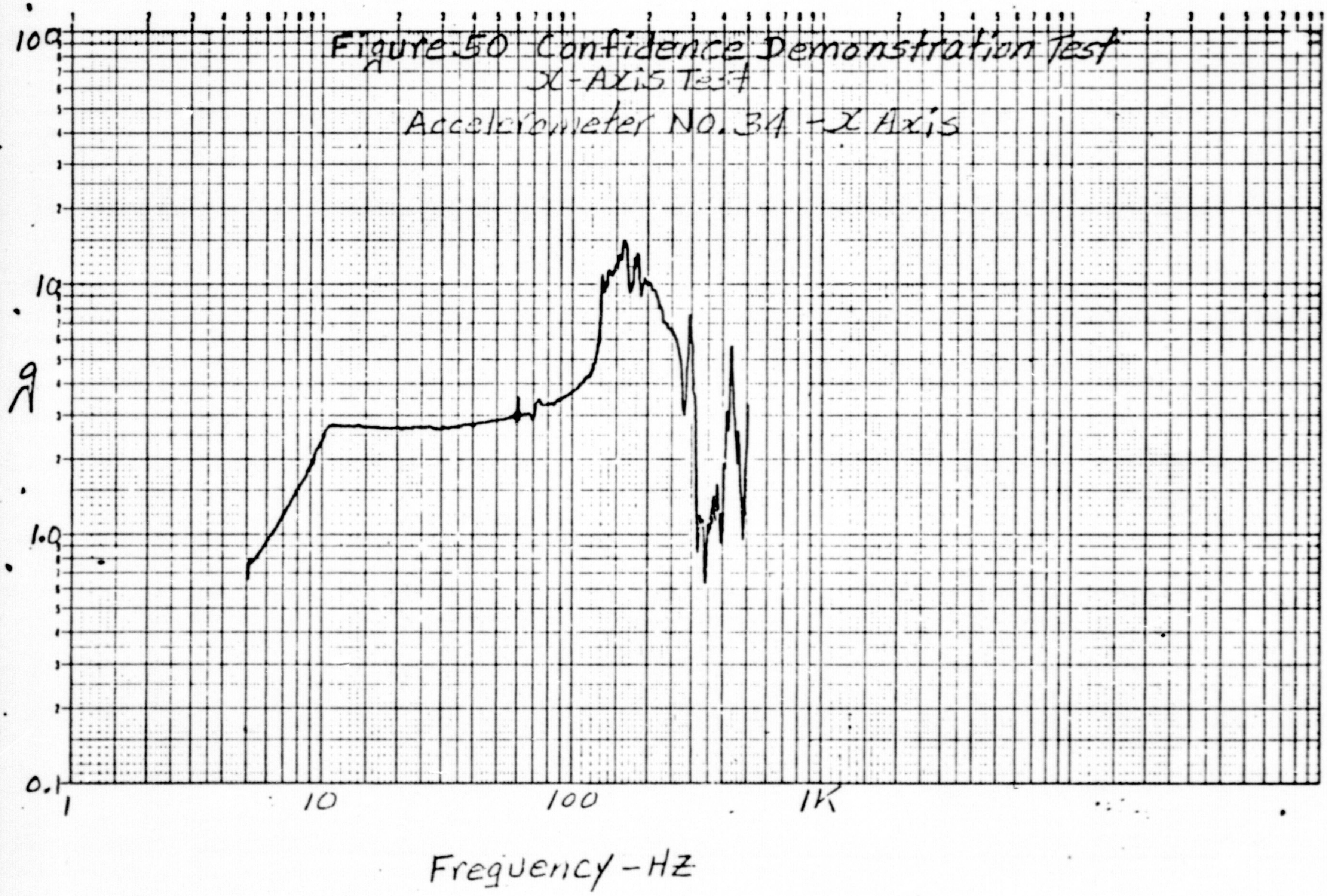


Figure 50 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 34 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - Hz
LOGARITHMIC 3 CYCLES X 5 CYCLES

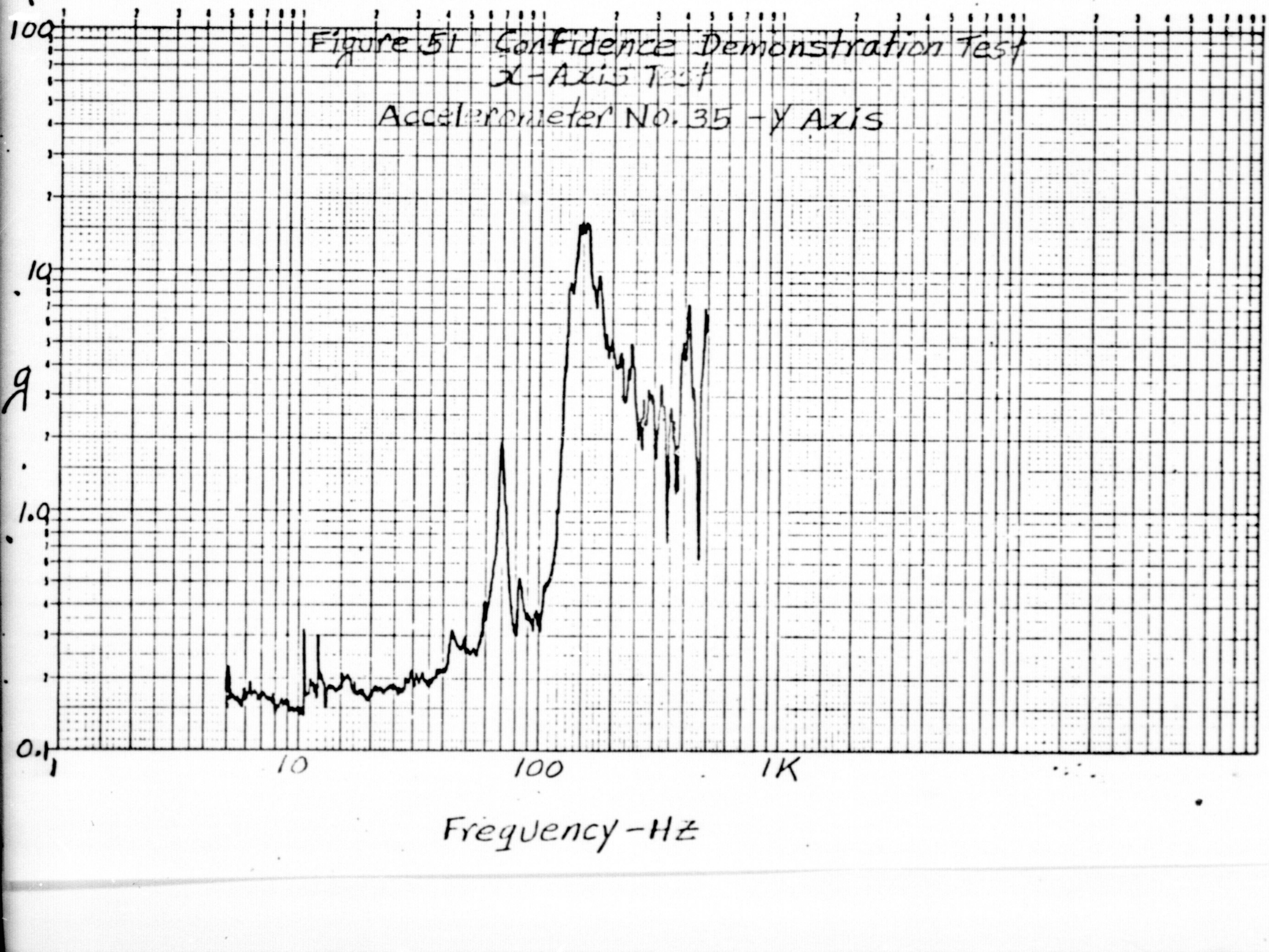


Figure 51 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 35 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

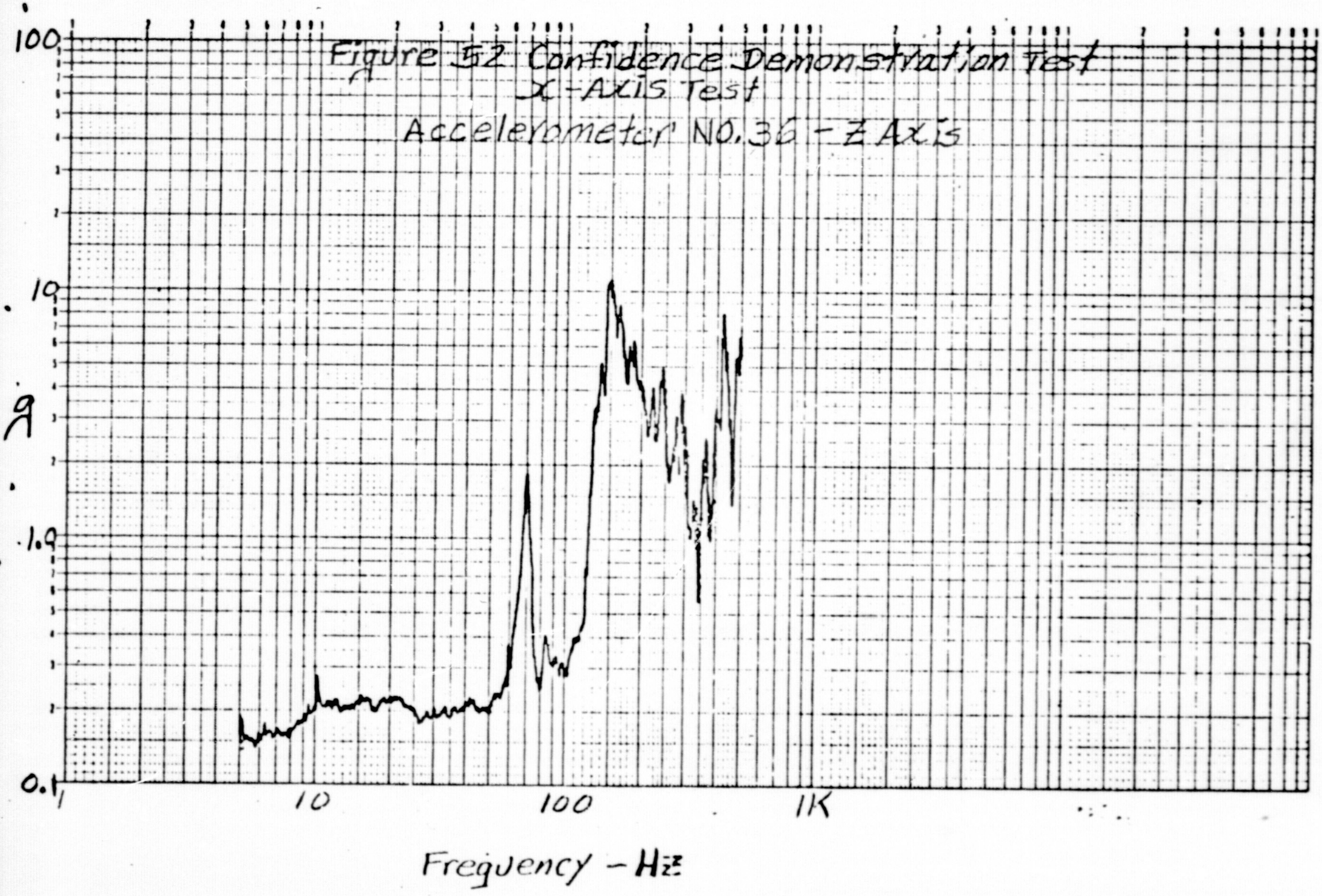


Figure 52 Confidence Demonstration Test
X-Axis Test
Accelerometer NO. 36 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522 MADE IN U.S.A.

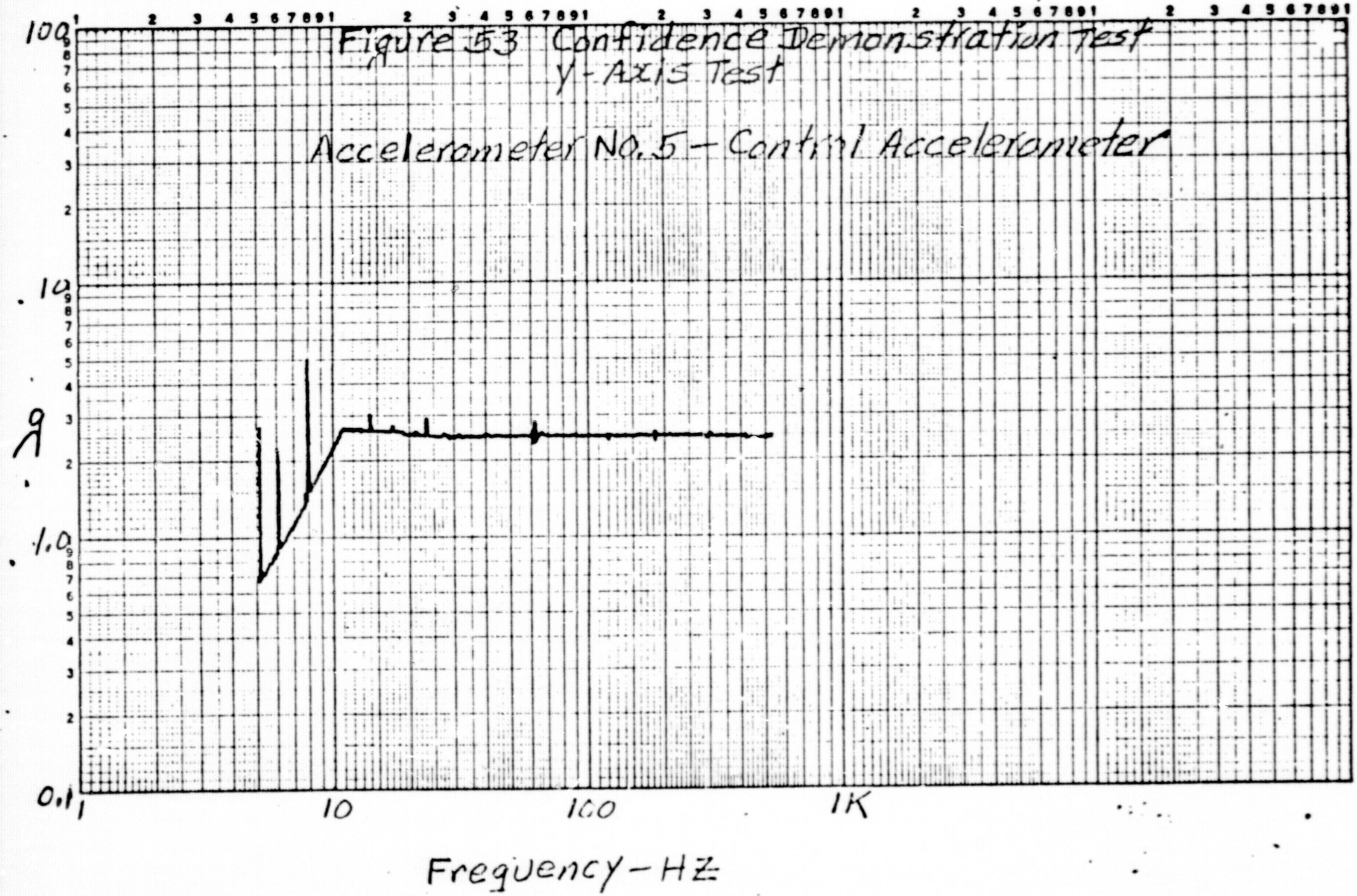
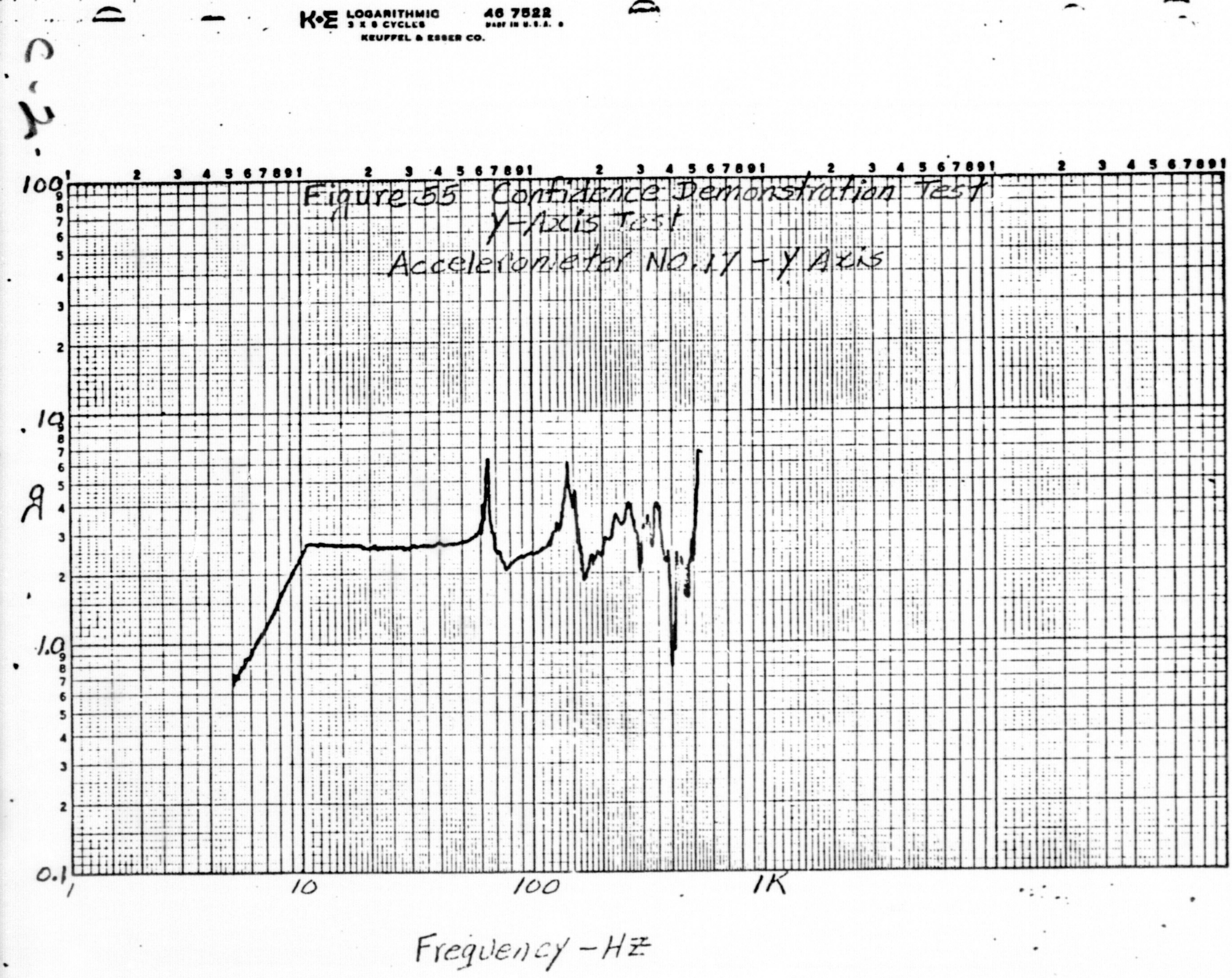


Figure 53 Confidence Demonstration Test
Y-Axis Test


K•E LOGARITHMIC 3 X 5 CYCLES
46 7522 MADE IN U.S.A.
KEUFFEL & ESSER CO.
Figure 54 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 16 - X Axis
100
.10
g
1.0
0.1
10
100
1K
Frequency - HZ

C-2.


K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522
Figure 55 Confidence Demonstration Test
Y-Axis Test
Accelerometer NO. 17 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

5

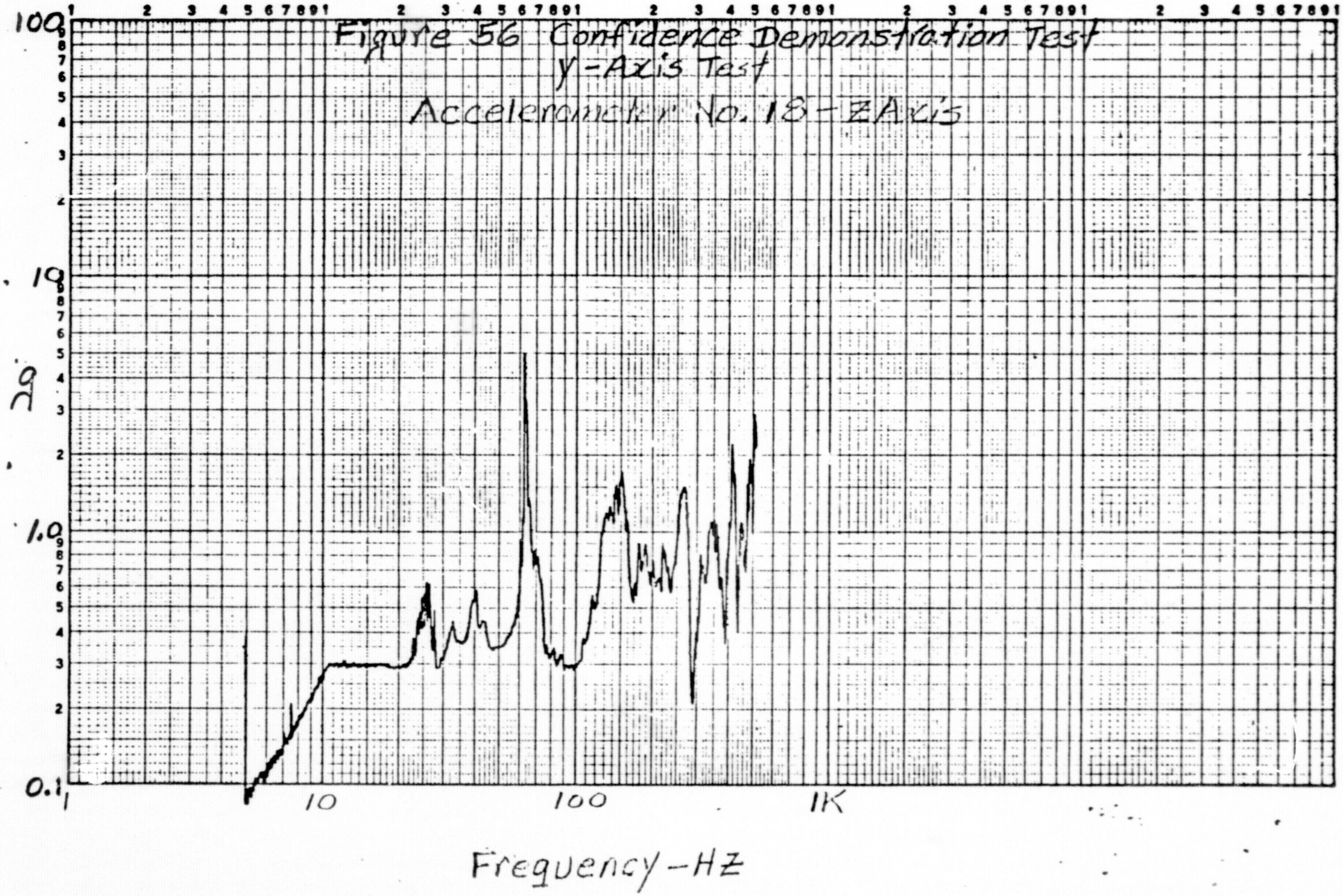


Figure 56 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 18 - Z Axis
100
10
g
1.0
0.1
10
100
1K
Frequency - HZ

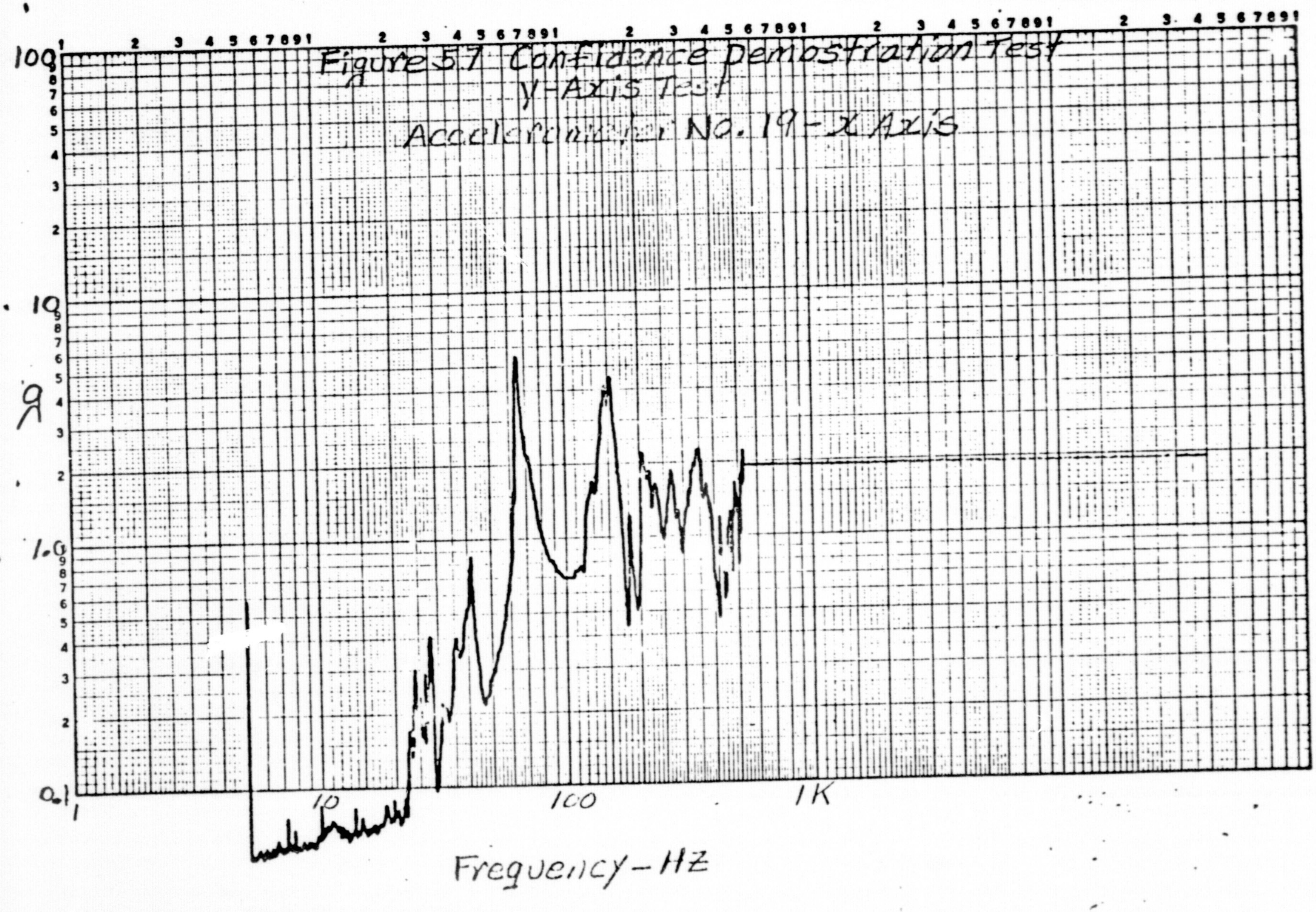
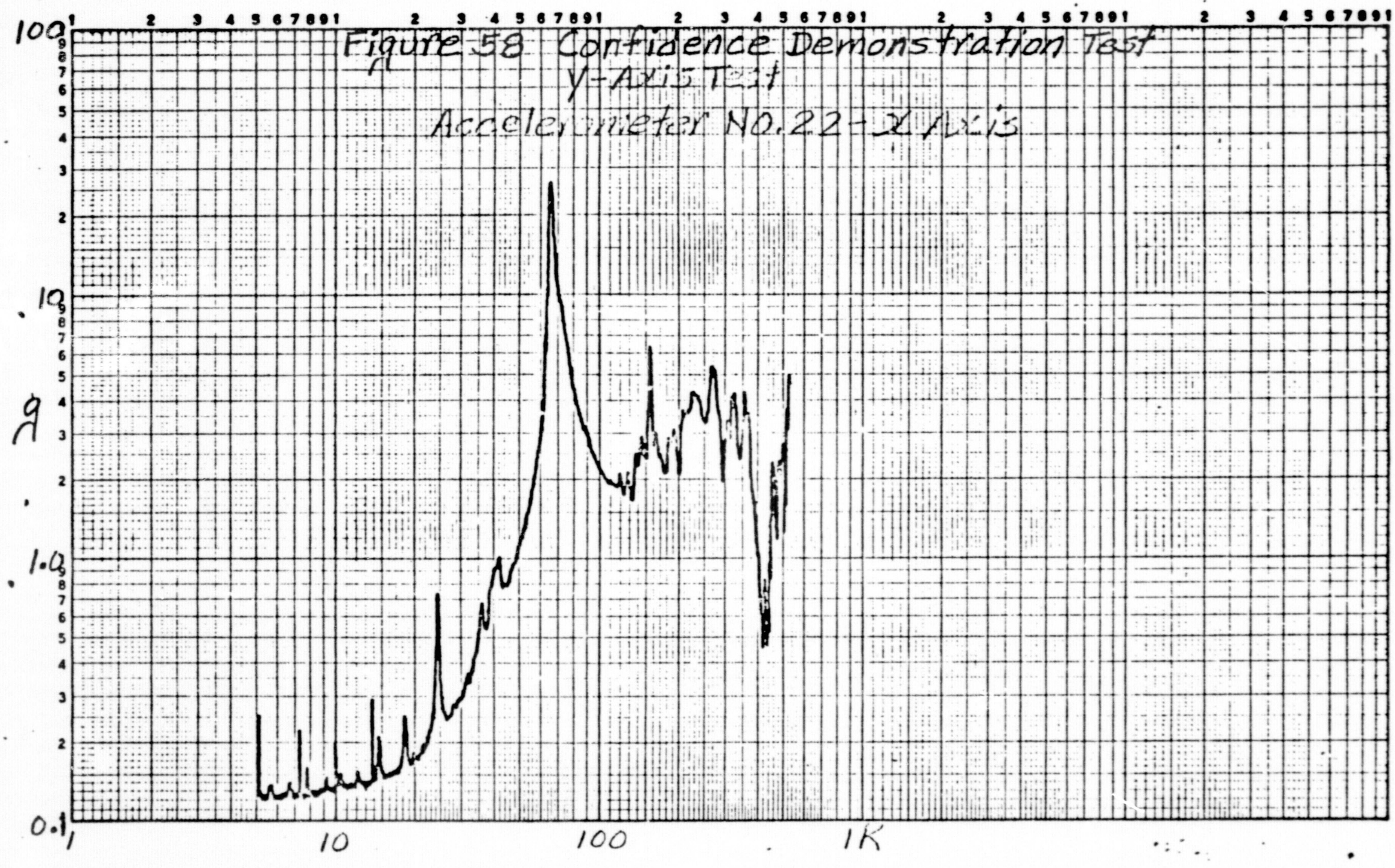


Figure 57 Confidence Demostration Test
Y-Axis Test
Accelerometer No. 19 - X Axis
g
Frequency - HZ
100
10
1.0
0.1
1
10
100
1K

Figure 58 Confidence Demonstration Test
Y-Axis Test
Accelerometer NO. 22 - X Axis



K•E LOGARITHMIC 3 X 5 CYCLES 46 7522 MADE IN U.S.A. KEUFFEL & ESSER CO.

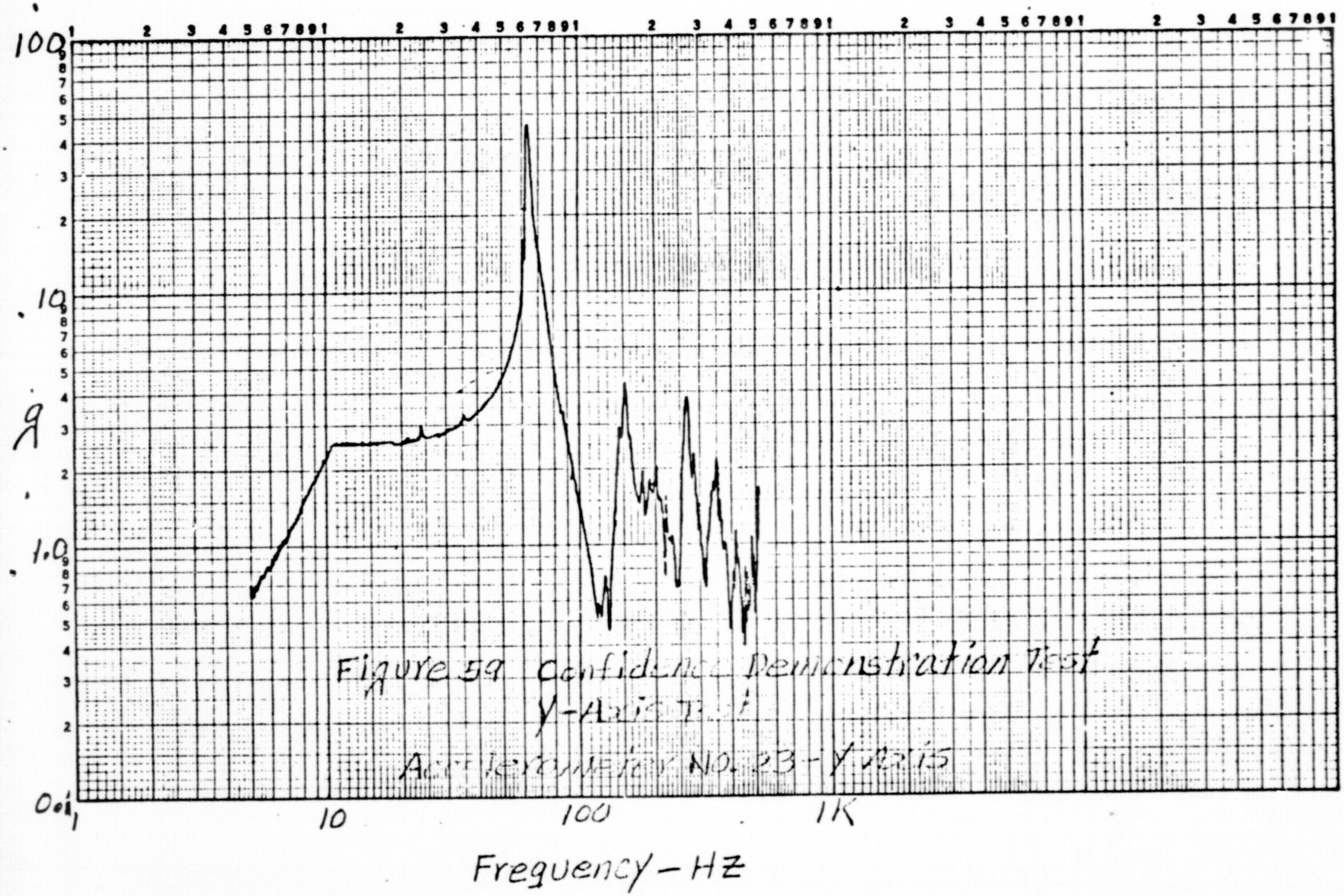


Figure 59 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 23 - Y Axis

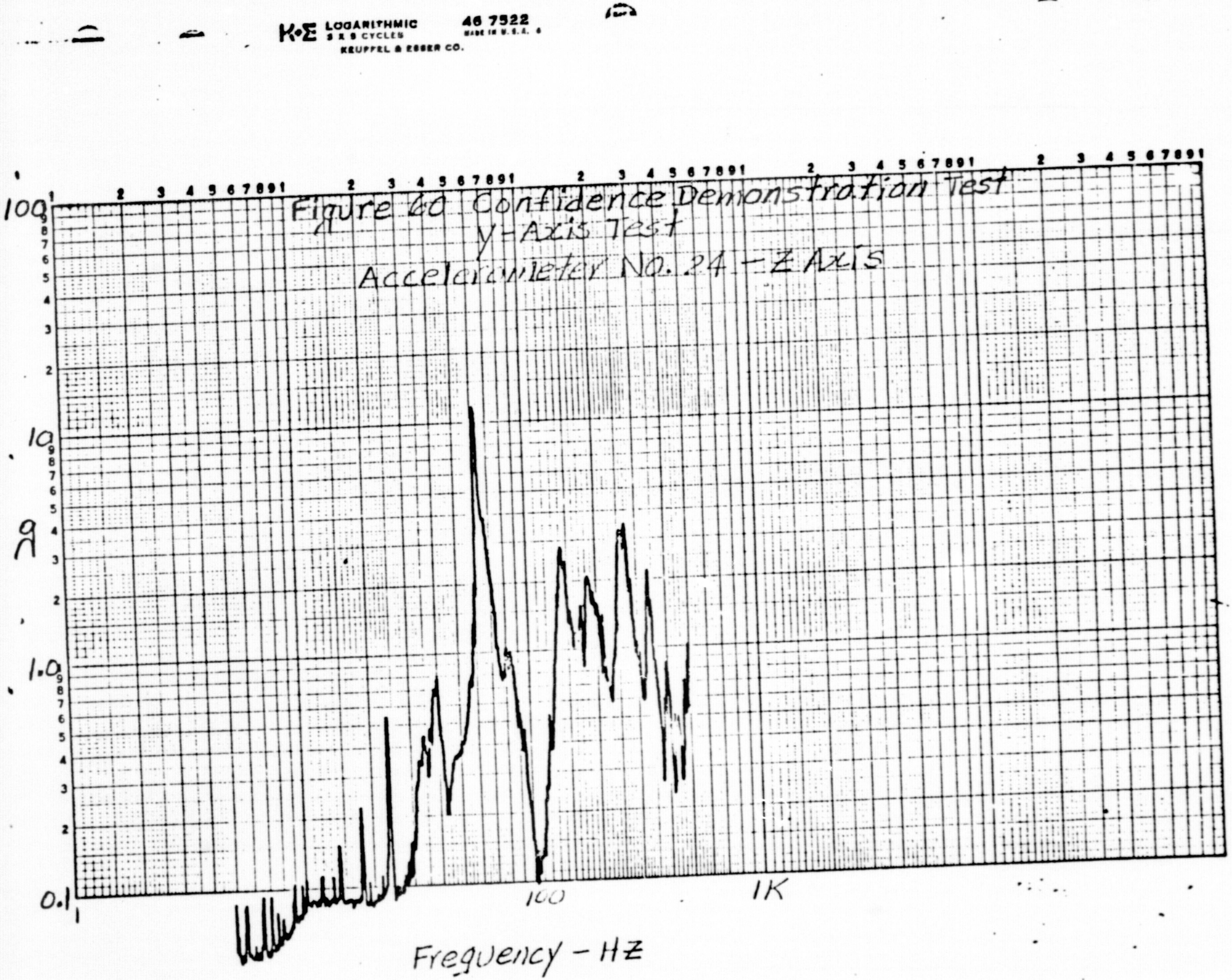
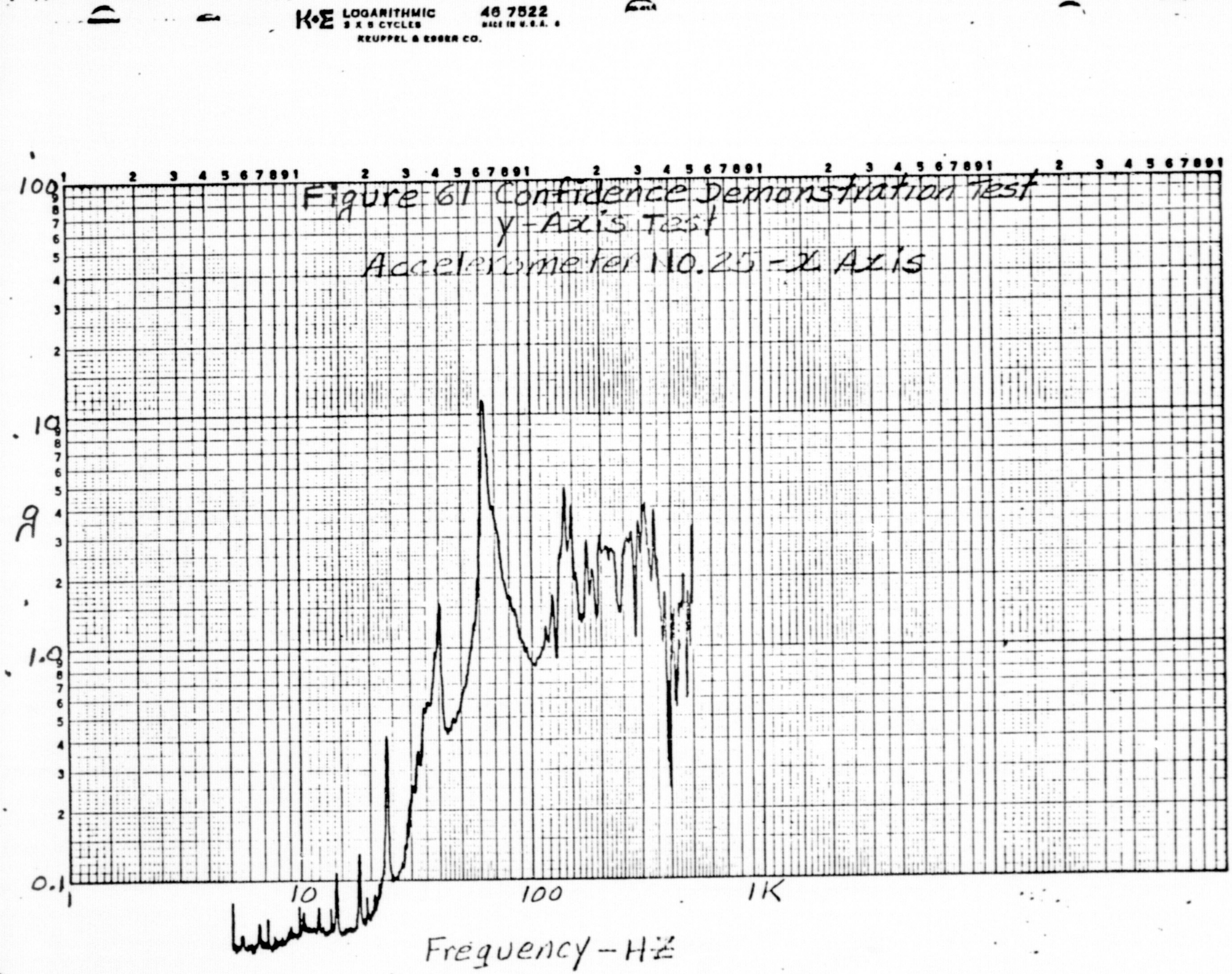
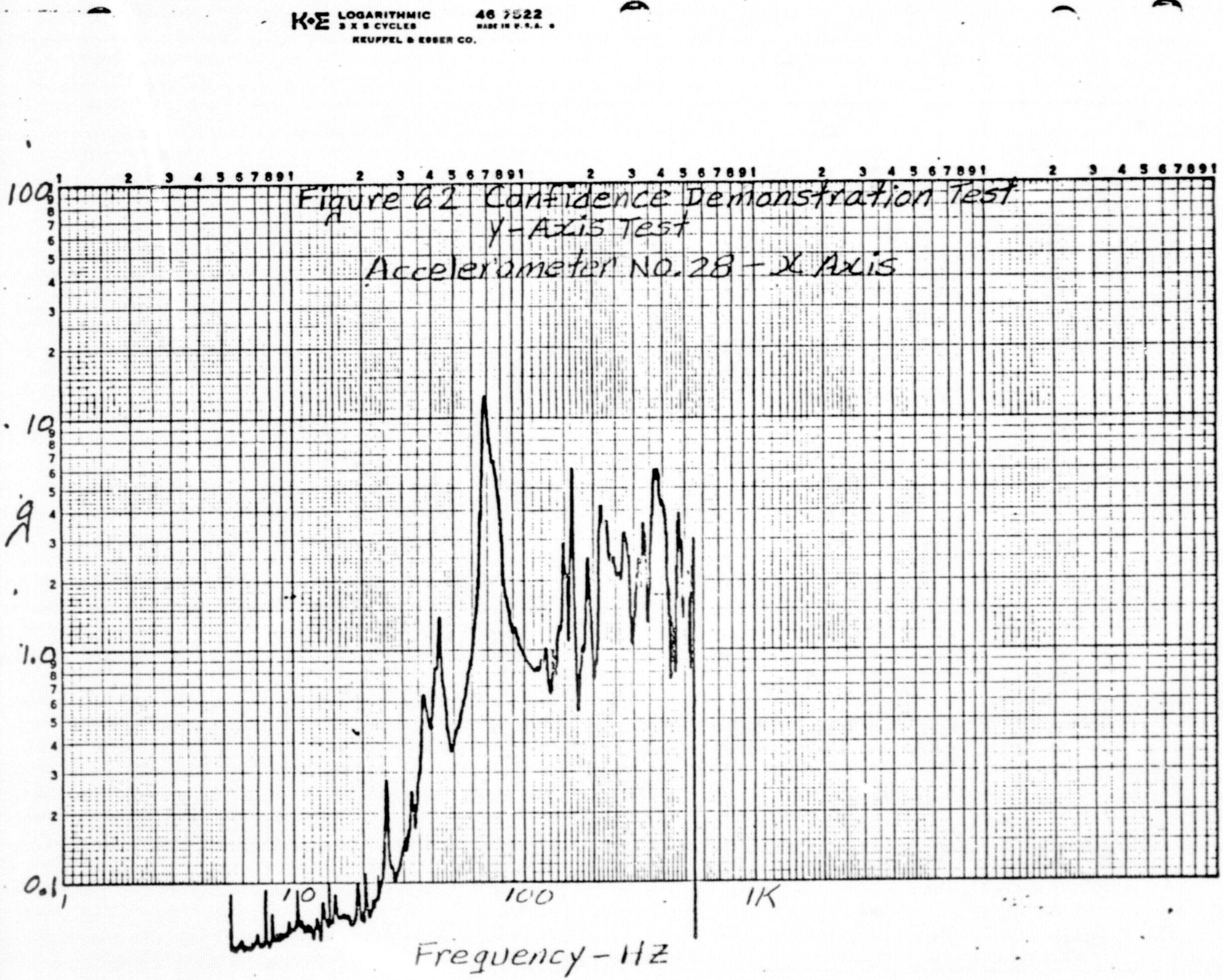


Figure 60 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 24 - Z Axis
100
10
1.0
0.1
g
100
1K
Frequency - HZ
K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO.
46 7522


K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO.
46 7522
Figure 61 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 25 - X Axis
100
10
1.0
0.1
g
10
100
1K
Frequency - Hz


K·E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522
Figure 62 Confidence Demonstration Test
Y-Axis Test
Accelerometer NO. 28 - X Axis
100
10
1.0
0.1
g
10
100
1K
Frequency - HZ

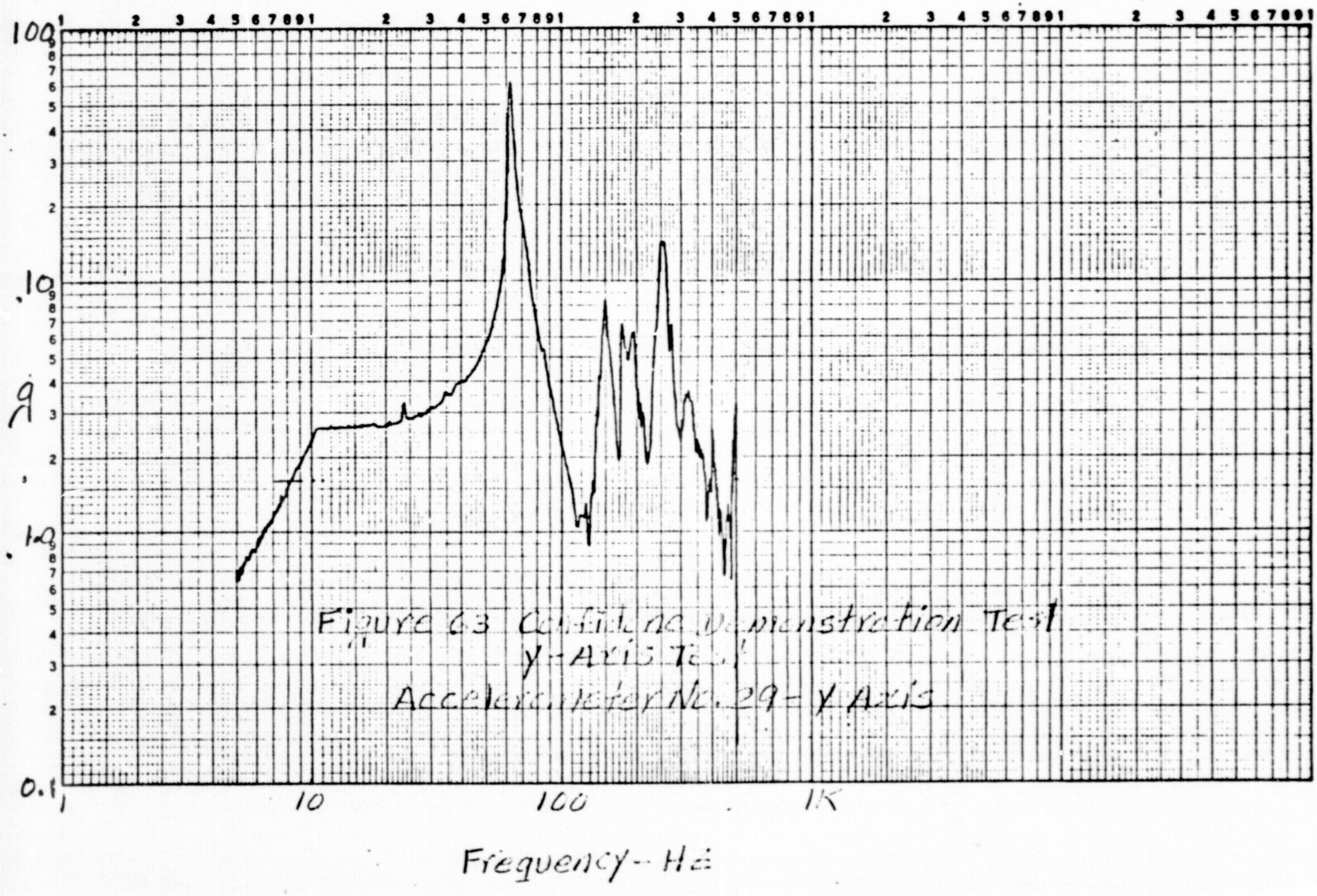


Figure 63 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 29 - Y Axis

K•E LOGARITHMIC 3 X 5 CYCLES 46 7522 MADE IN U.S.A. KEUFFEL & ESSER CO.

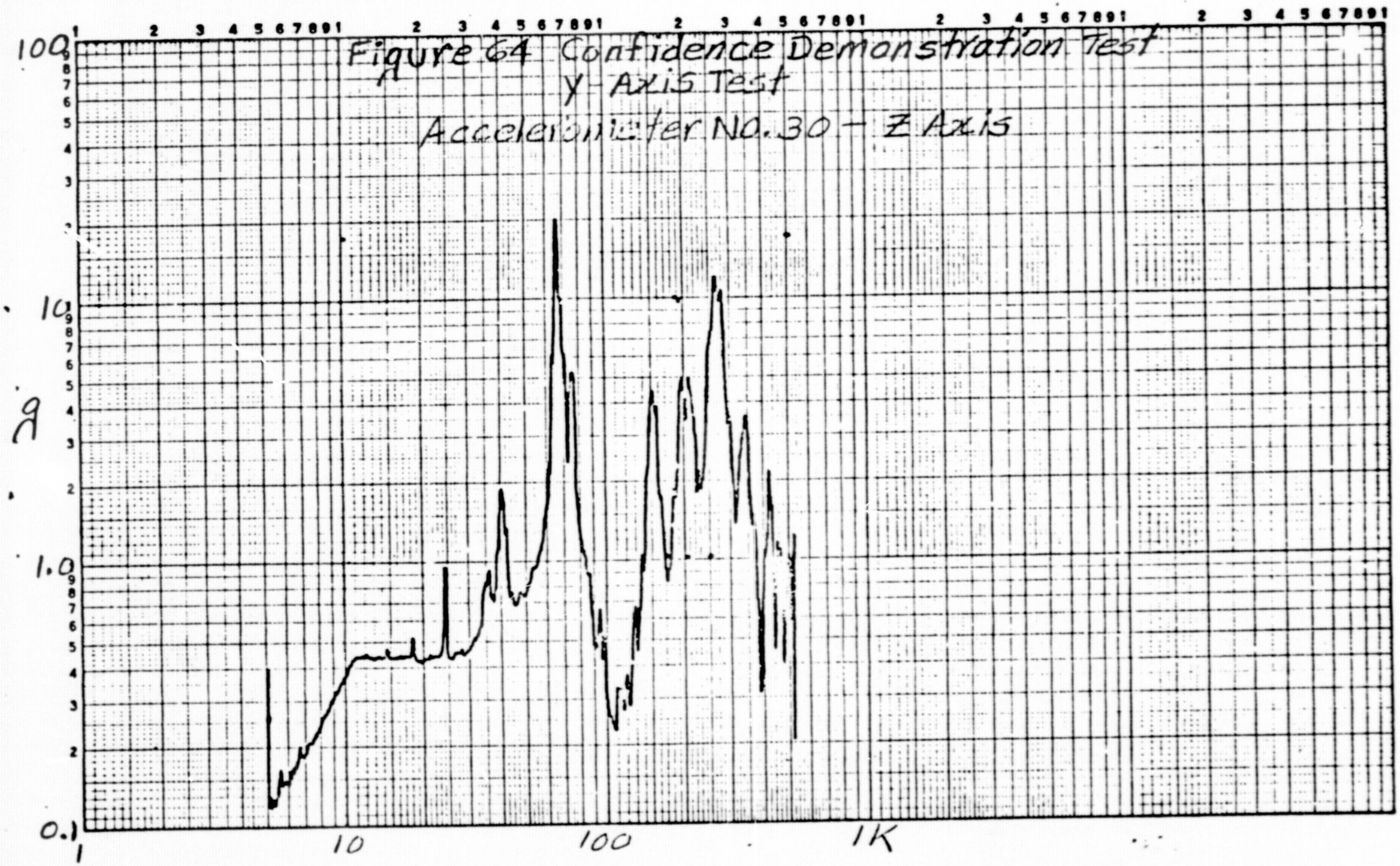


Figure 64 Confidence Demonstration Test
Y Axis Test
Accelerometer No. 30 - Z Axis

LOGARITHMIC 3 CYCLES X 5 CYCLES

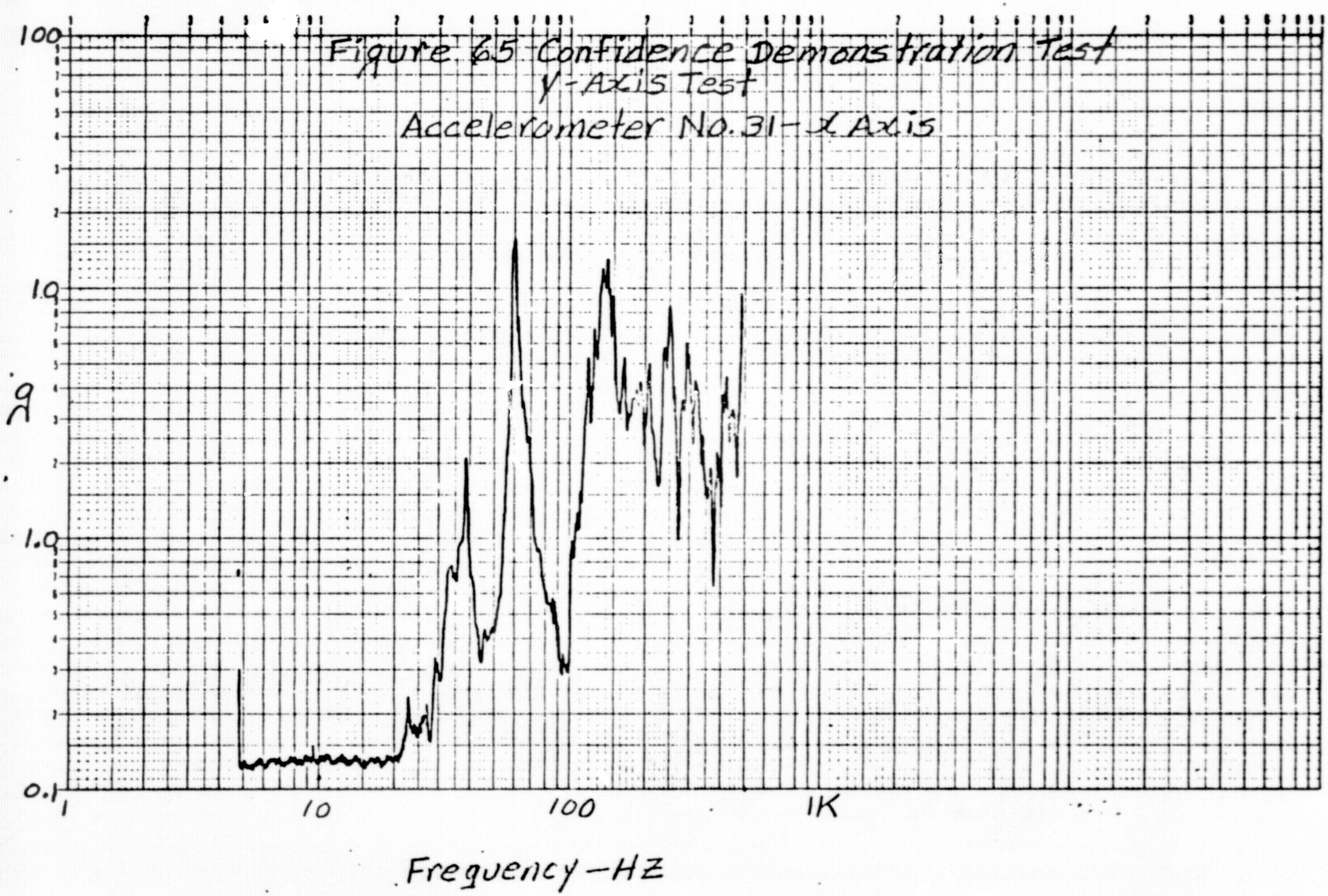
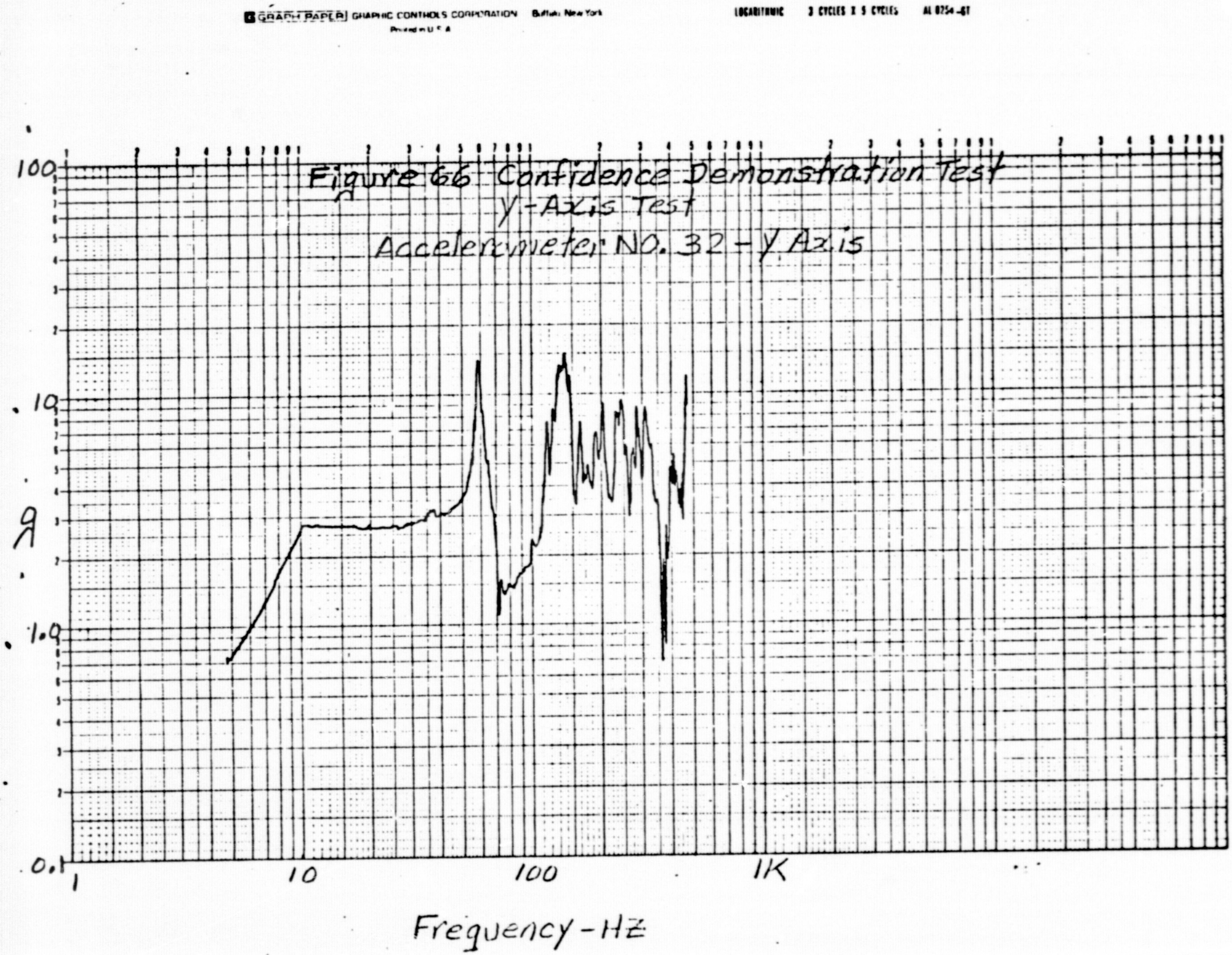


Figure 65 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 31- X Axis


GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
Printed in U.S.A.
LOGARITHMIC 3 CYCLES X 5 CYCLES AL 0754-GT
Figure 66 Confidence Demonstration Test
Y-Axis Test
Accelerometer NO. 32 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

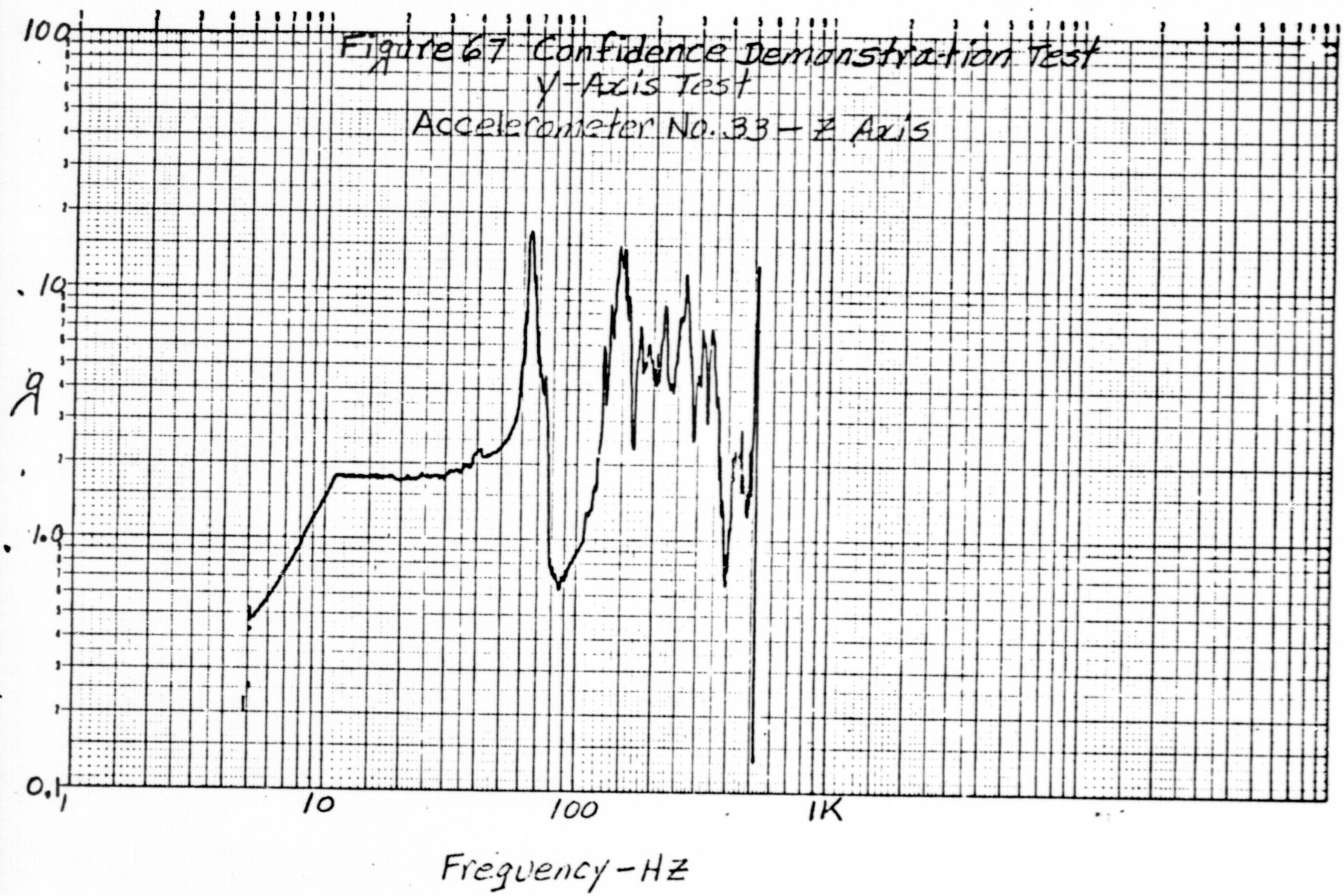
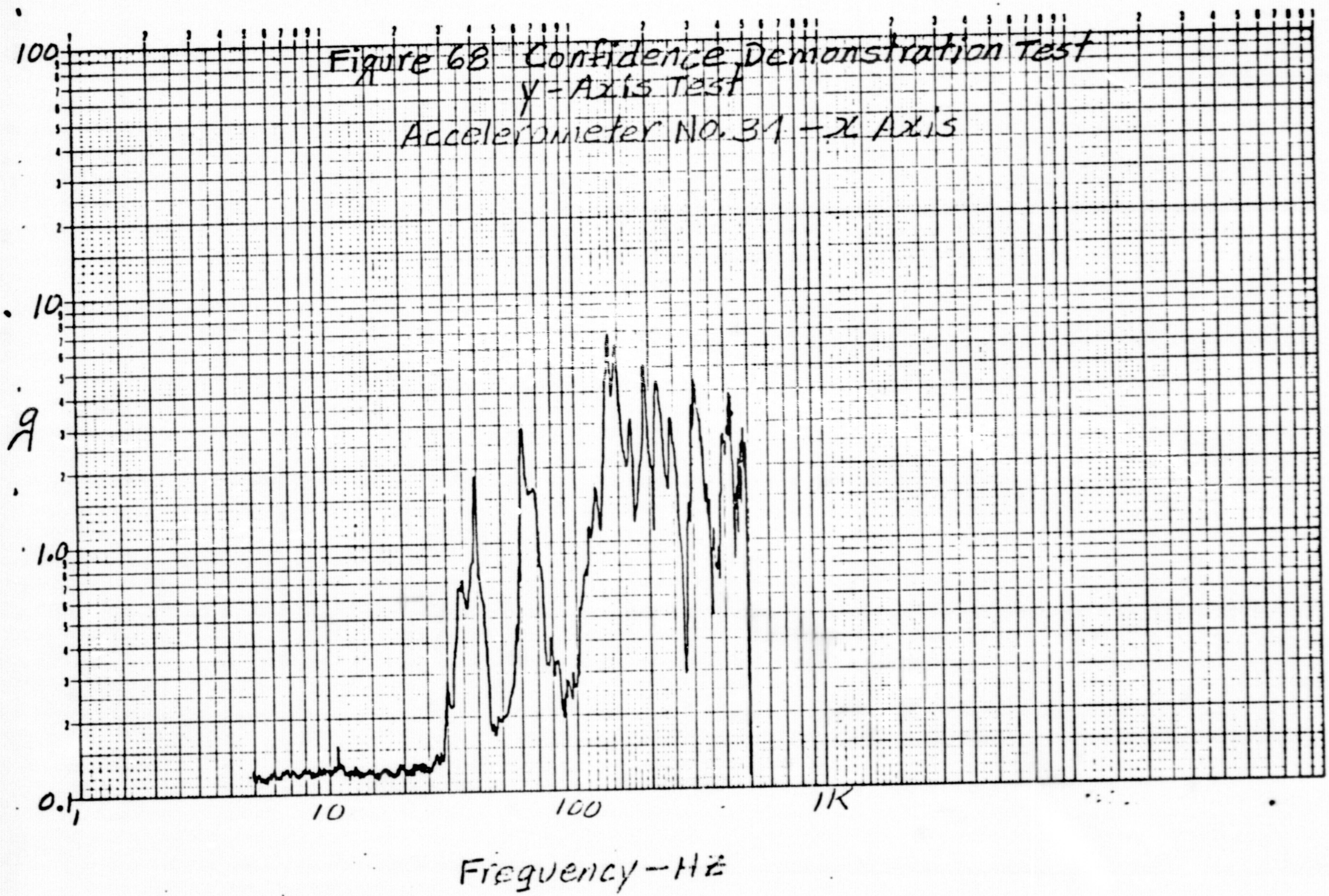


Figure 67 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 33 – Z Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency – HZ

Figure 68 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 31 - X Axis



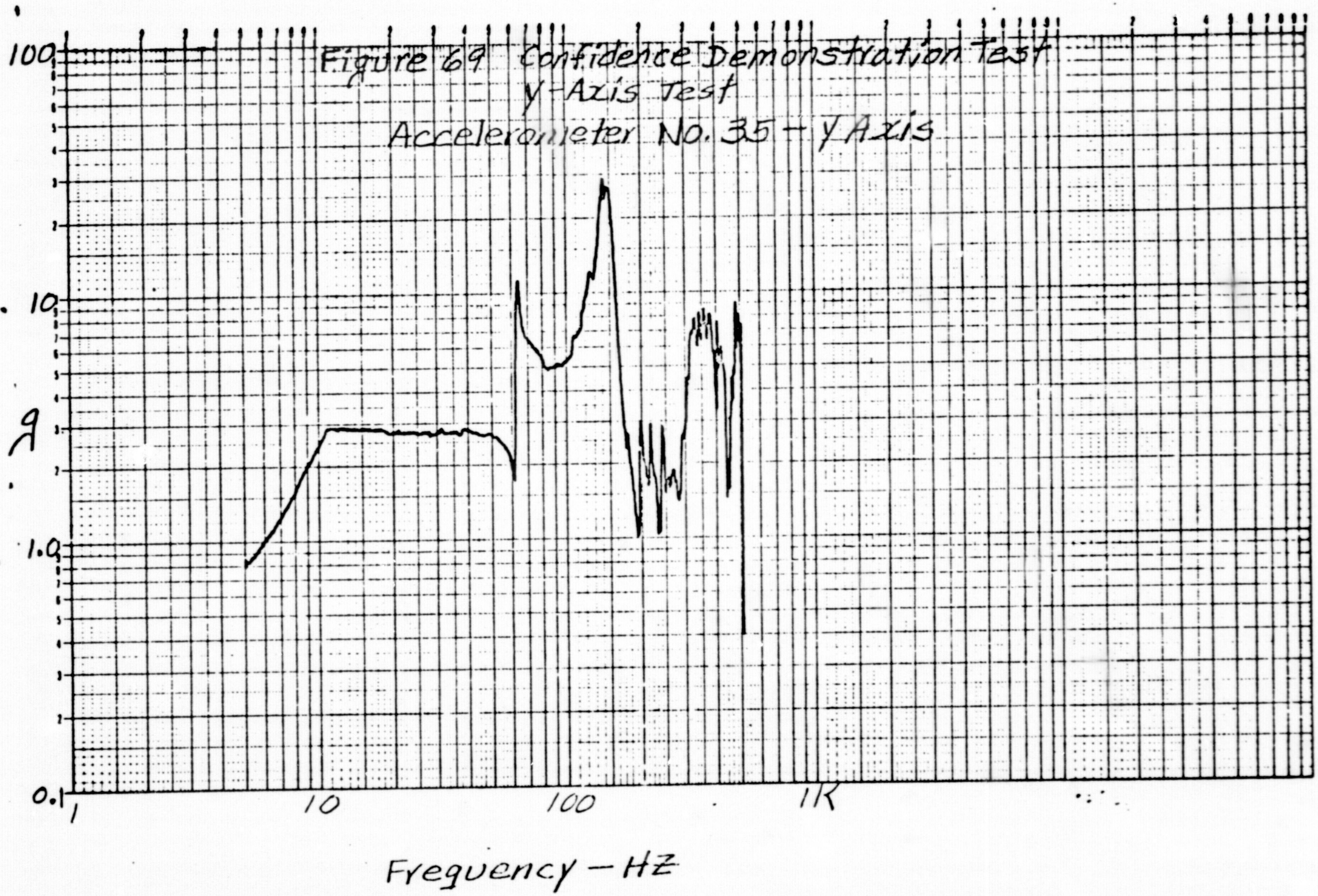


Figure 69 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 35 – Y Axis

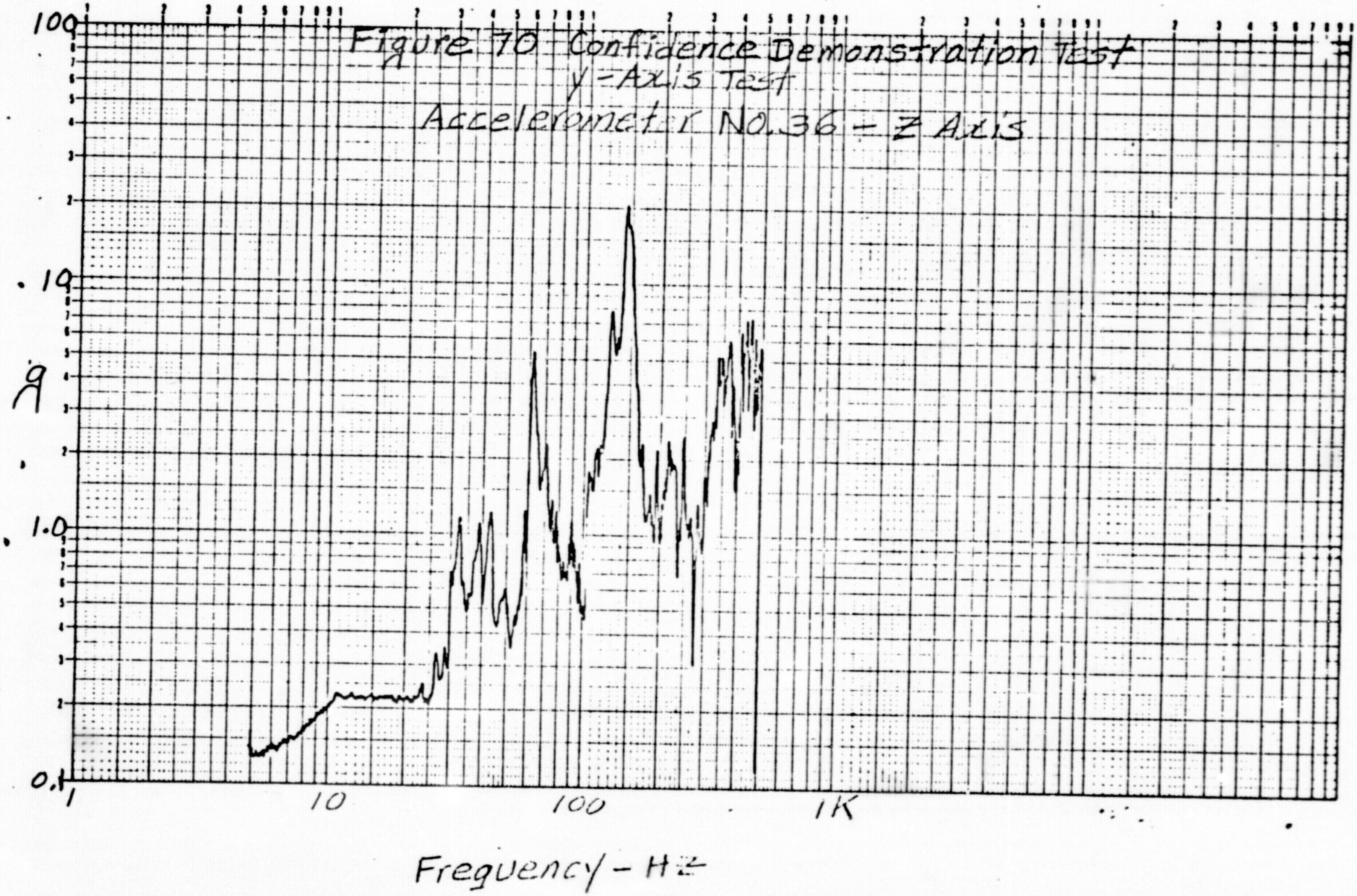


Figure 70 Confidence Demonstration Test
Y-Axis Test
Accelerometer No. 36 - Z Axis

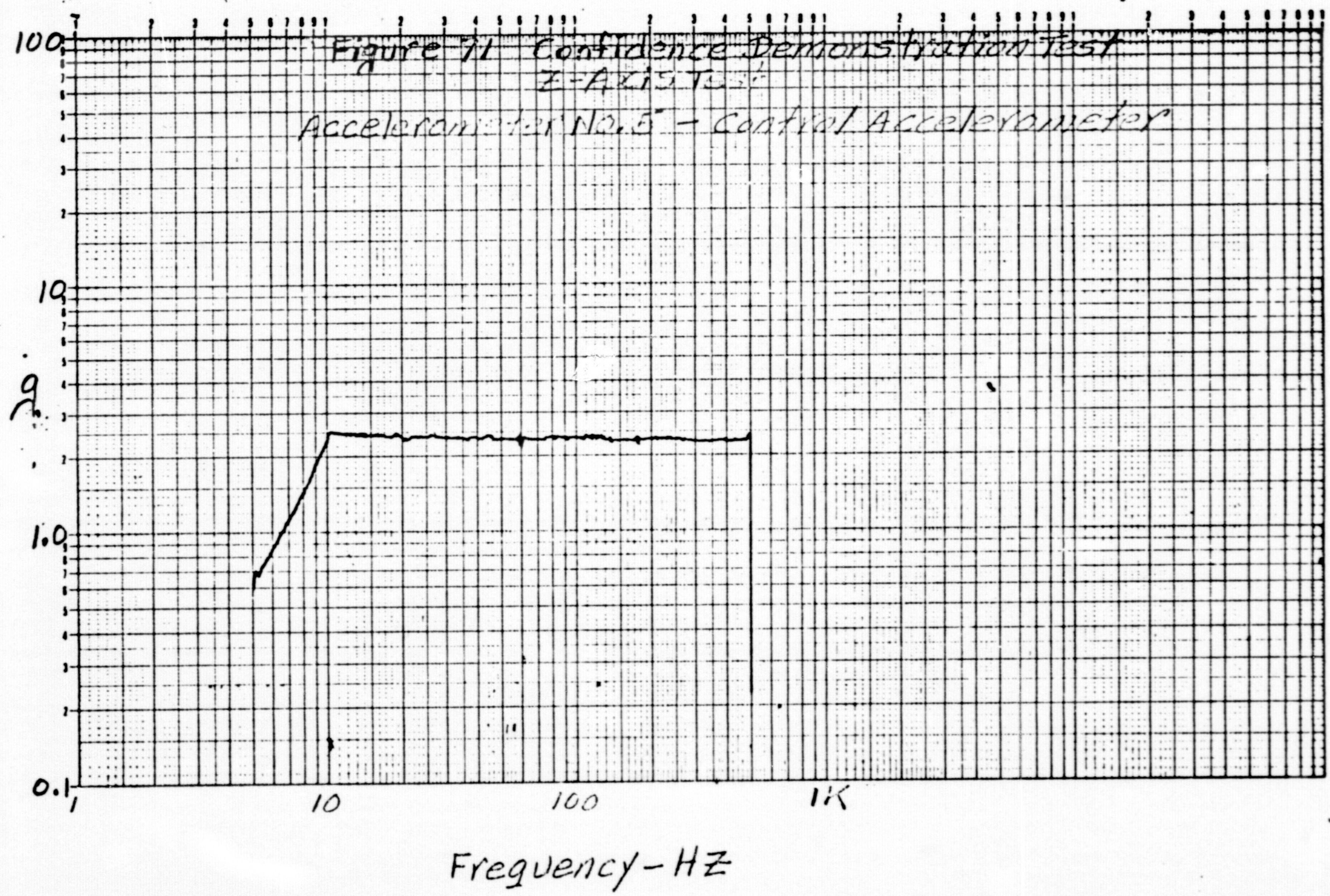
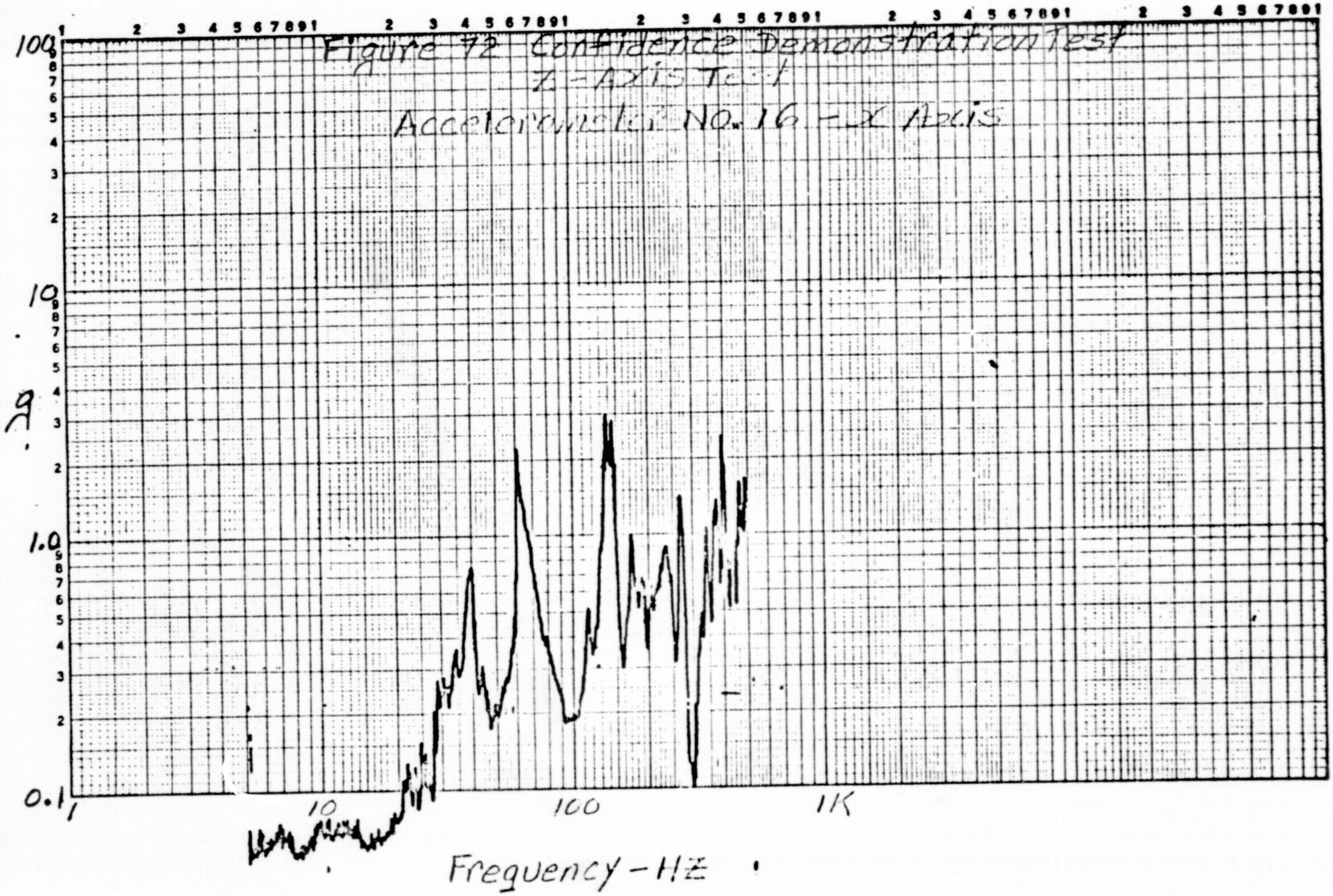
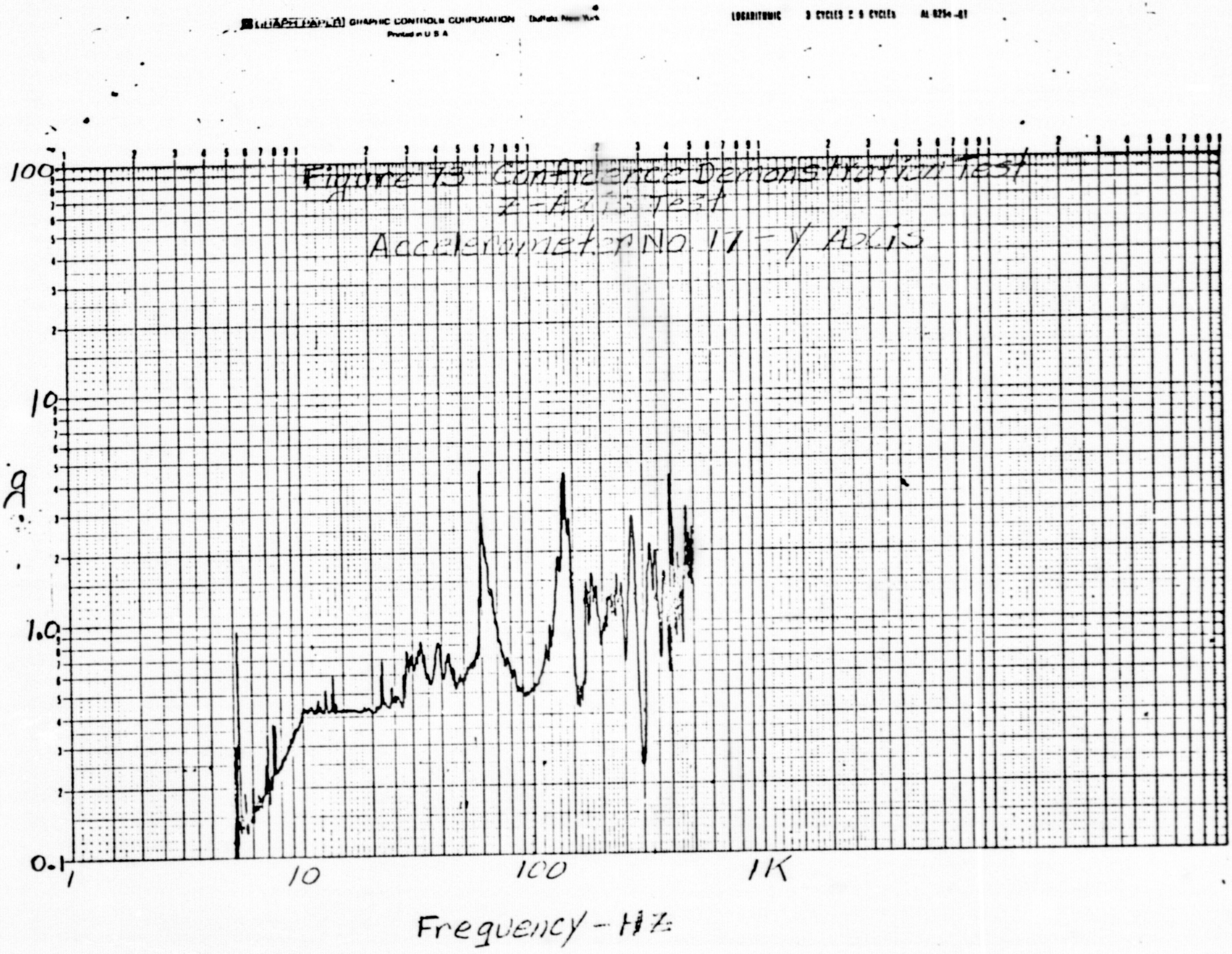


Figure 71 Confidence Demonstration Test
Z-Axis Test
Accelerometer No.5 - Control Accelerometer
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ

K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522 MADE IN U.S.A.




GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
Printed in U.S.A.
LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 73 Confidence Demonstration Test
Z-Axis Test
Accelerometer No 17 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - HZ

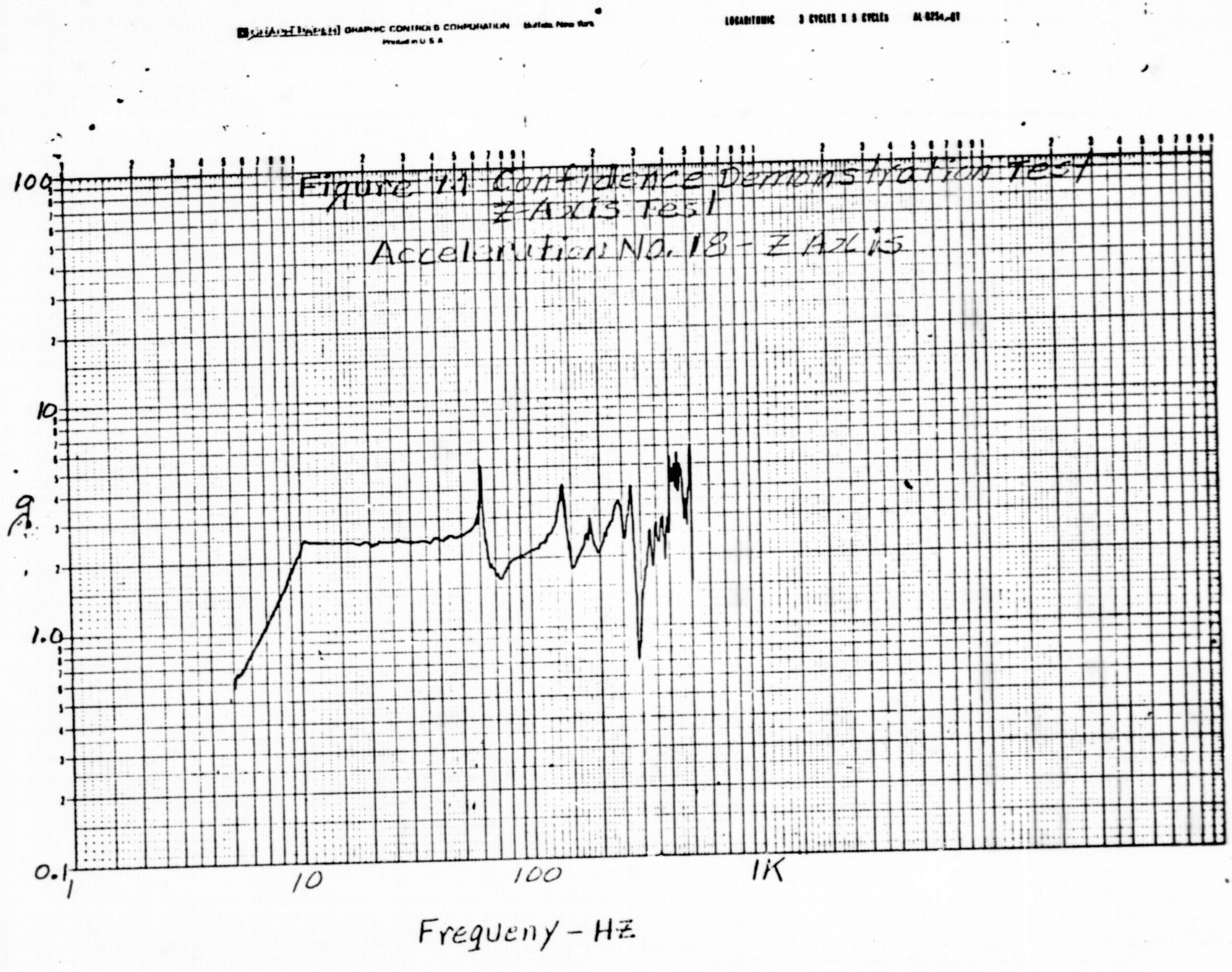


Figure 7.1 Confidence Demonstration Test
Z-Axis Test
Acceleration No. 18 - Z Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequeny - HZ

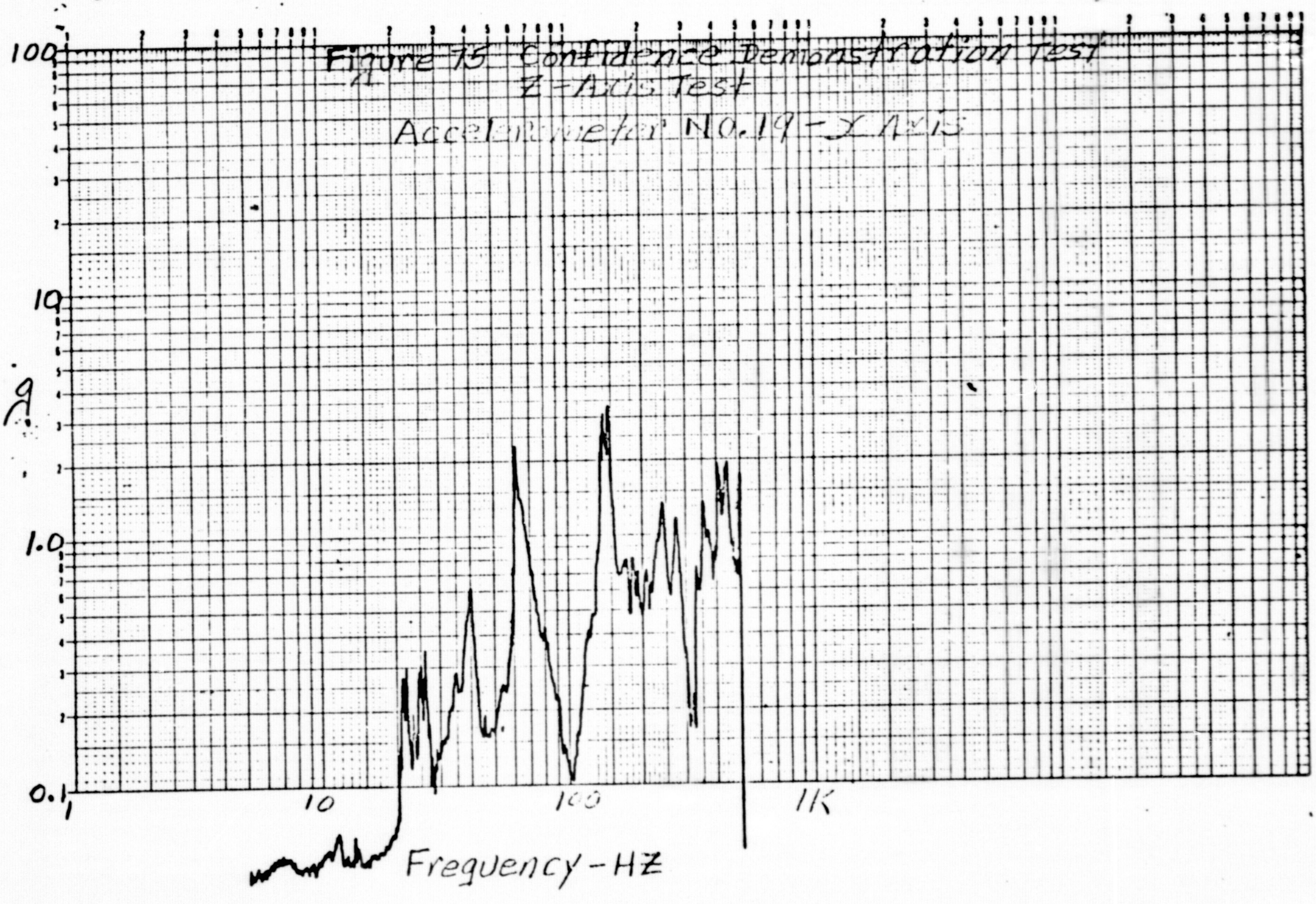
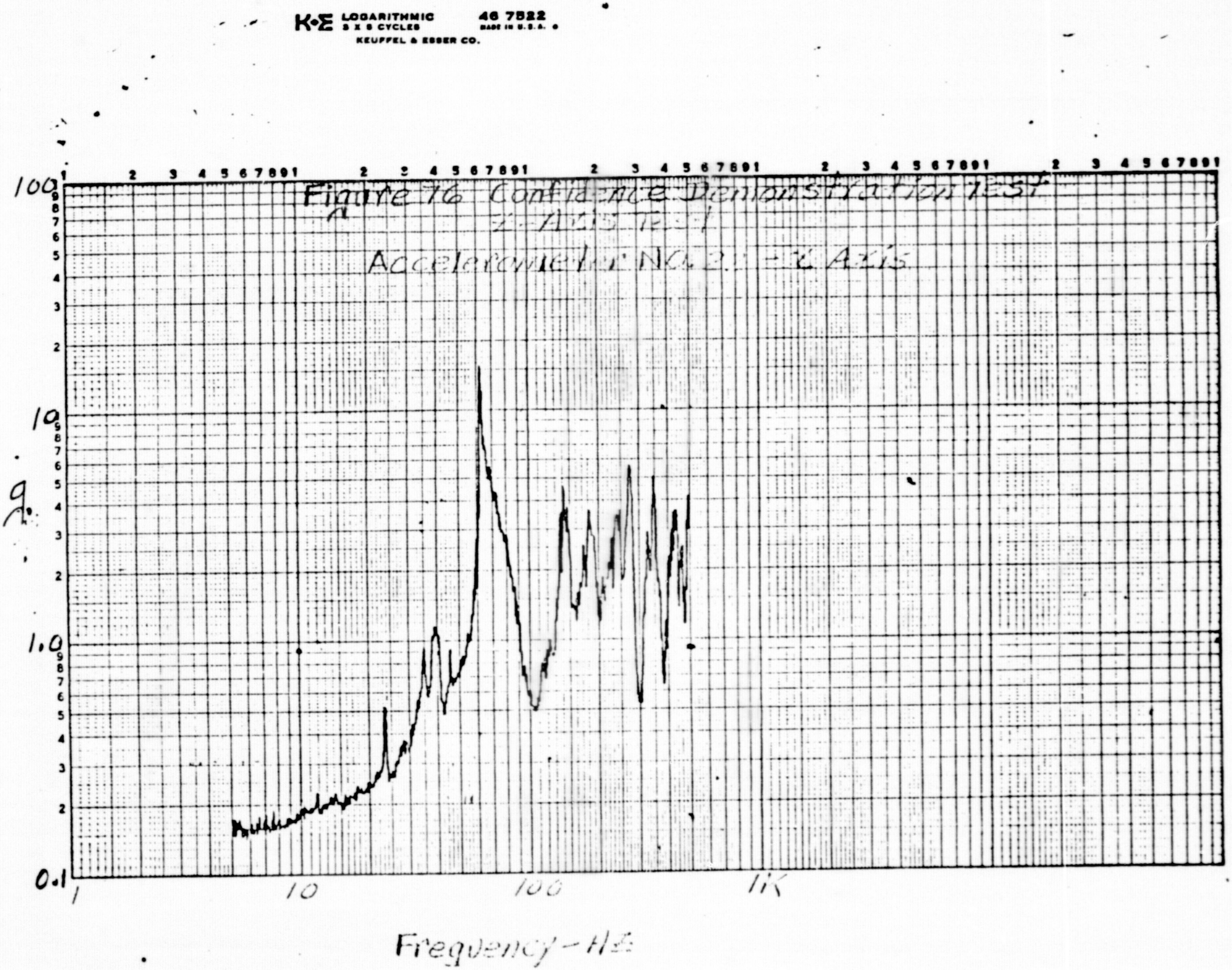


Figure 15 Confidence Demonstration Test
Z-Axis Test
Accelerometer No. 19 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ


K•E LOGARITHMIC 3 X 5 CYCLES 46 7522 MADE IN U.S.A.
KEUFFEL & ESSER CO.
Figure 76 Confidence Demonstration Test
Accelerometer No. 2 - Z Axis
g
100
10
1.0
0.1
1
10
100
1K
Frequency - Hz

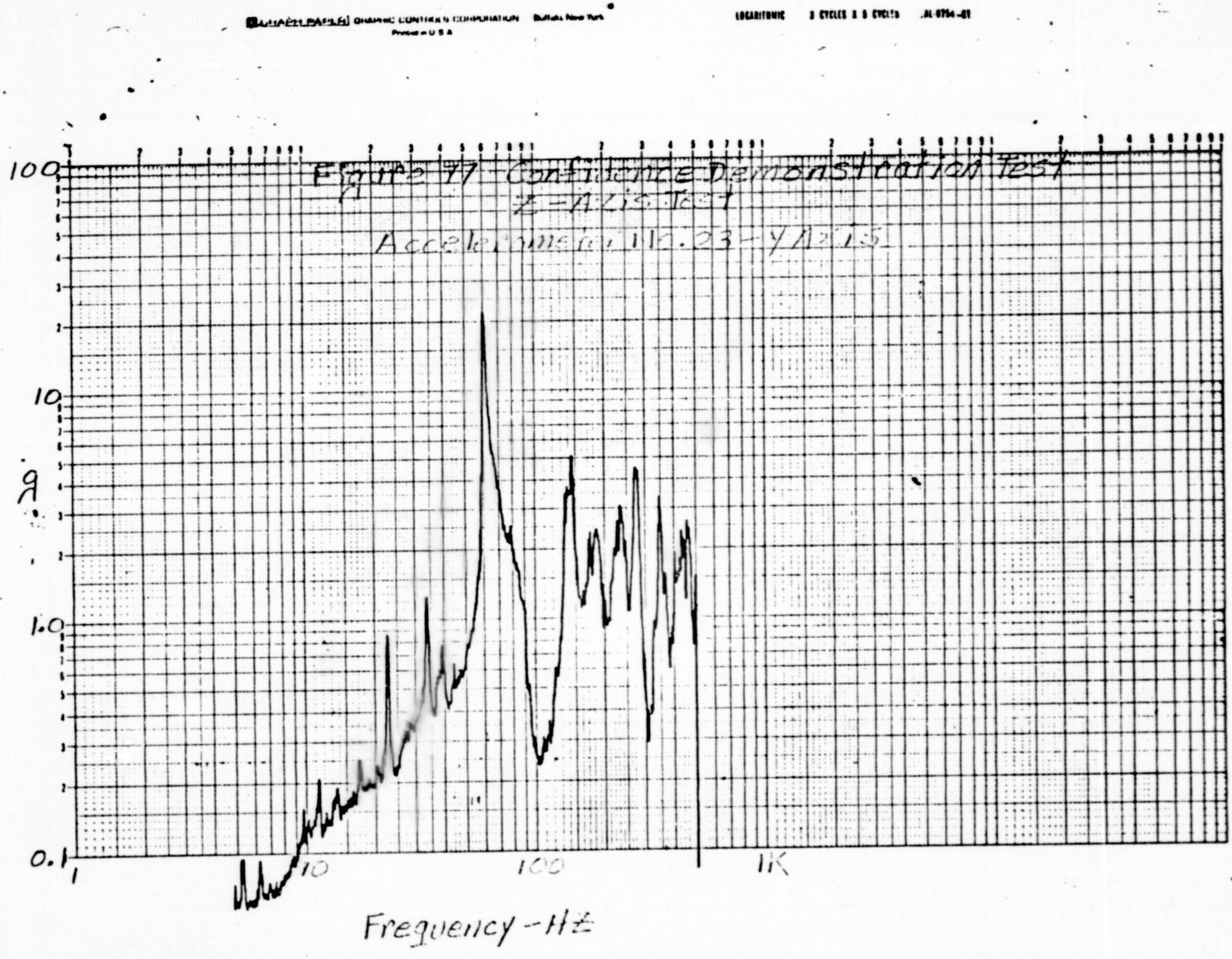
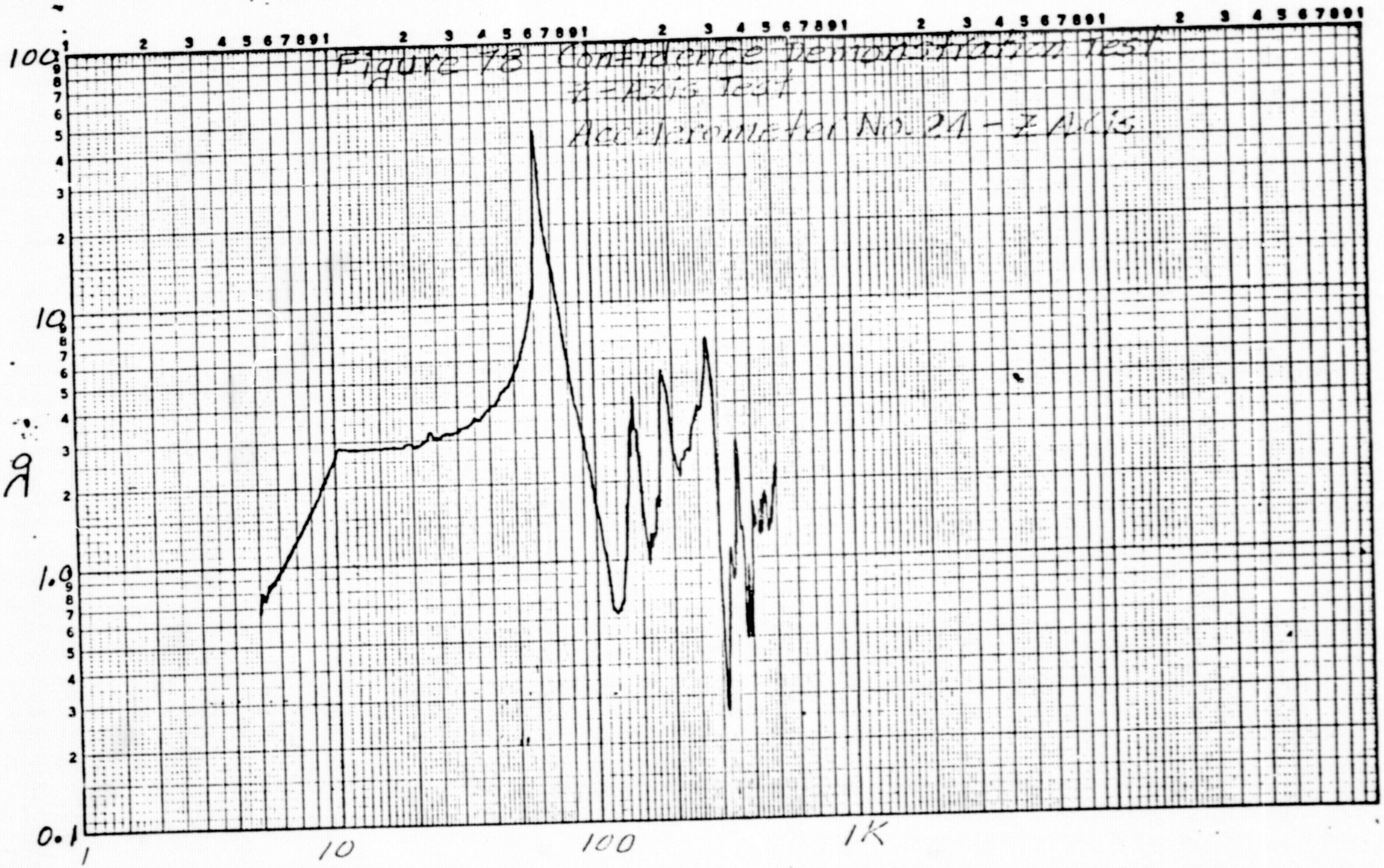
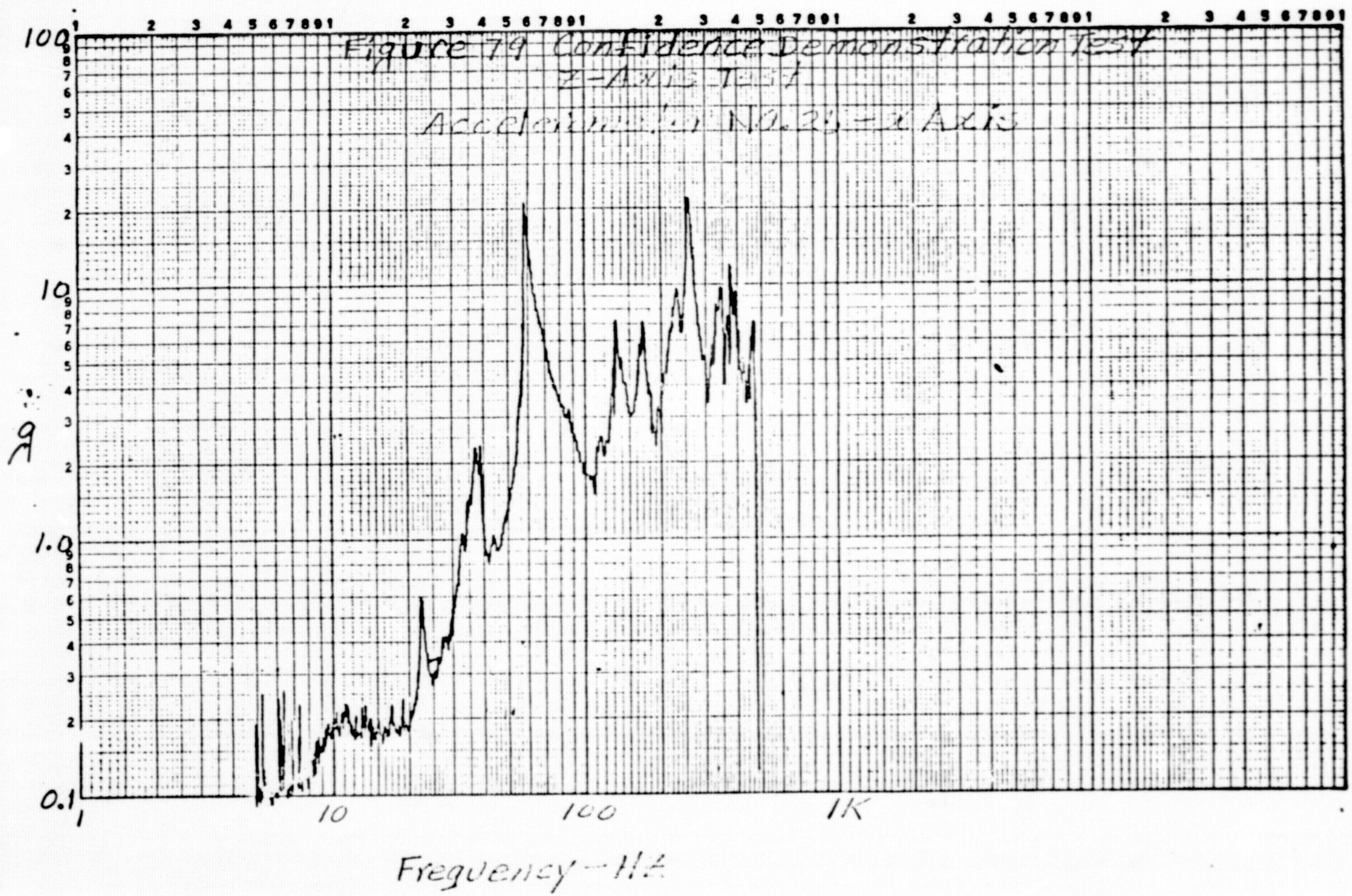
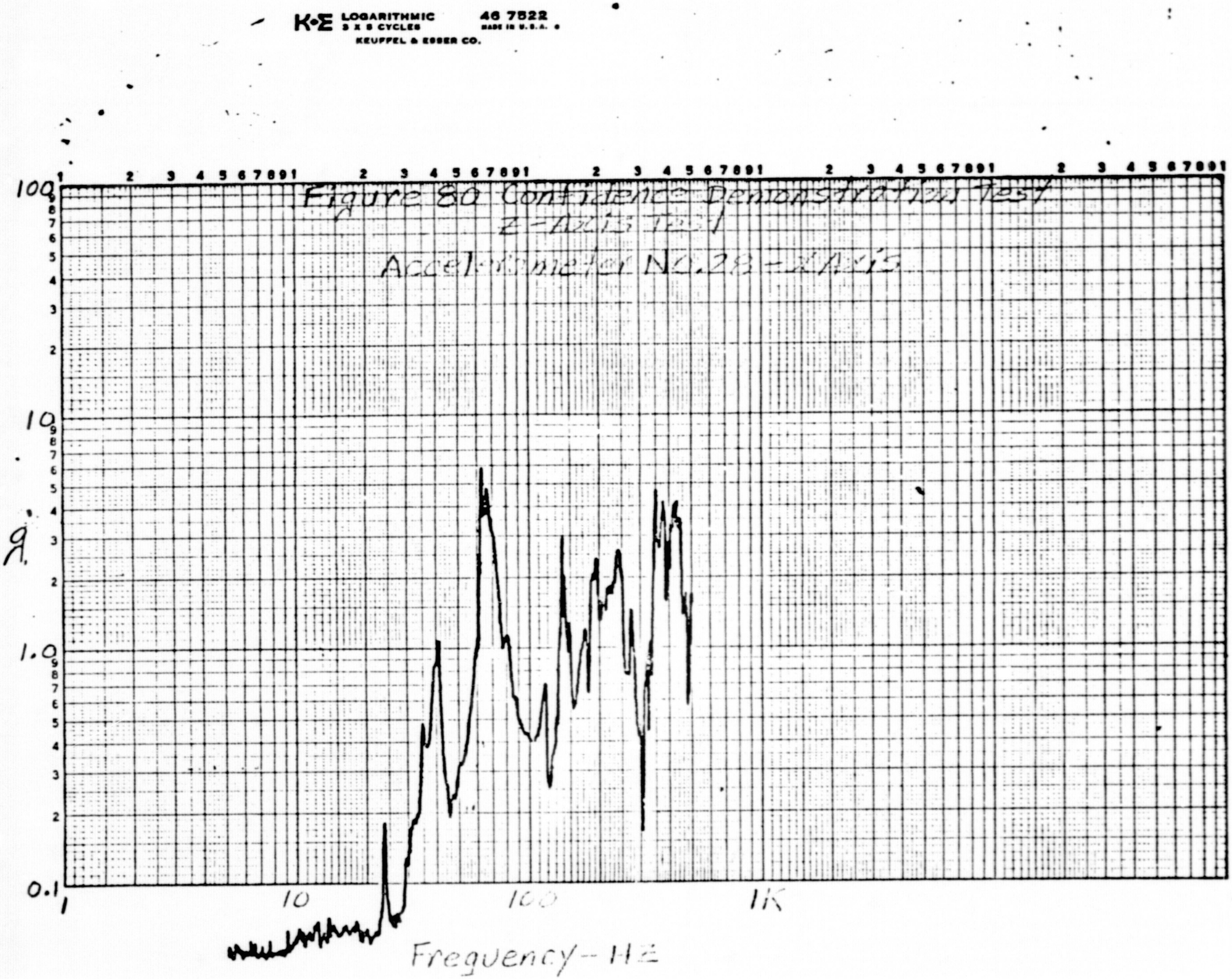


Figure 77 Confidence Demonstration Test
Z-Axis Test
Accelerometer No. 23 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz
GRAPHIC CONTROLS CORPORATION Buffalo, New York
Printed in U.S.A.
LOGARITHMIC 3 CYCLES X 5 CYCLES

K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522 MADE IN U.S.A.

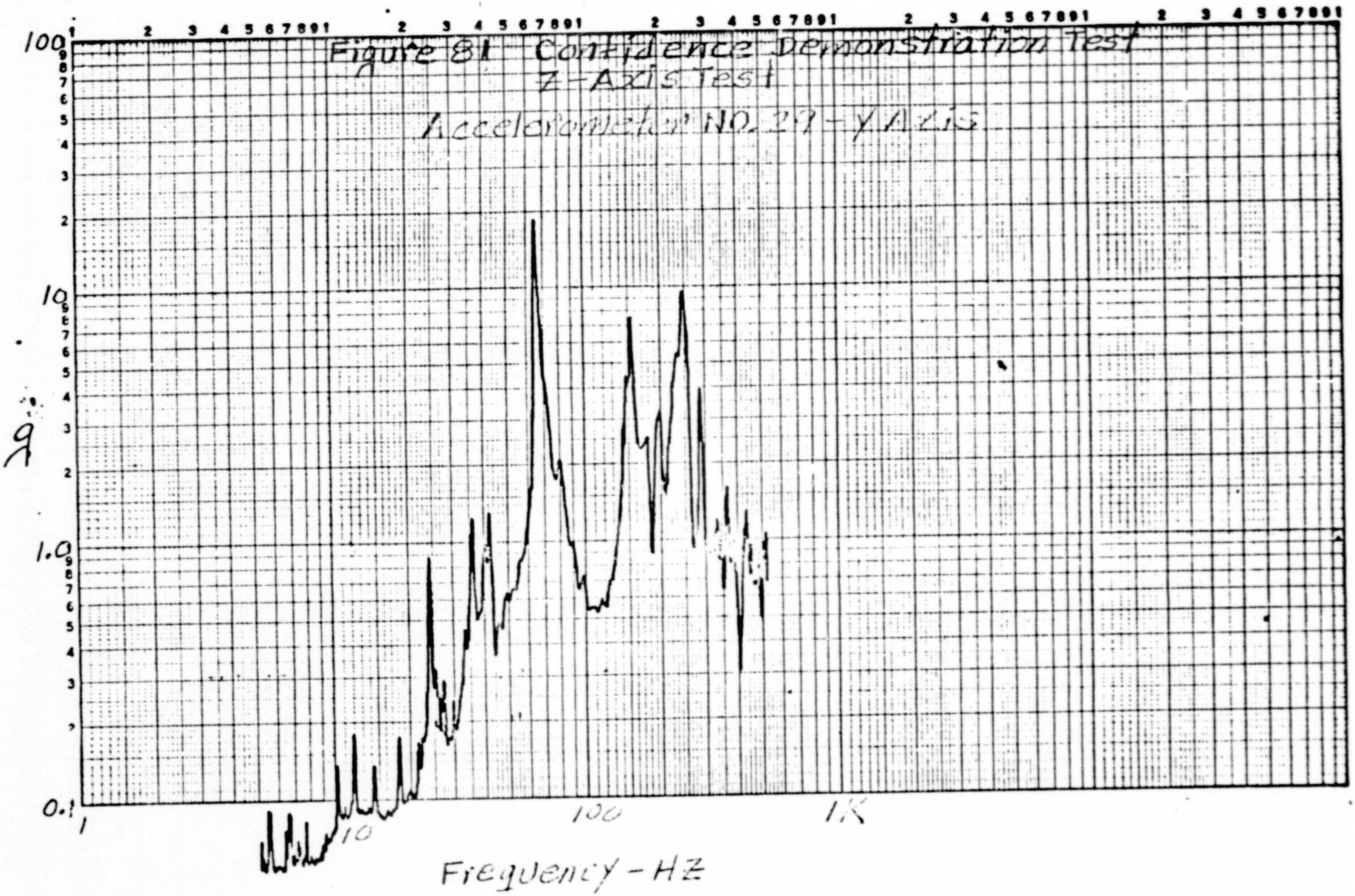


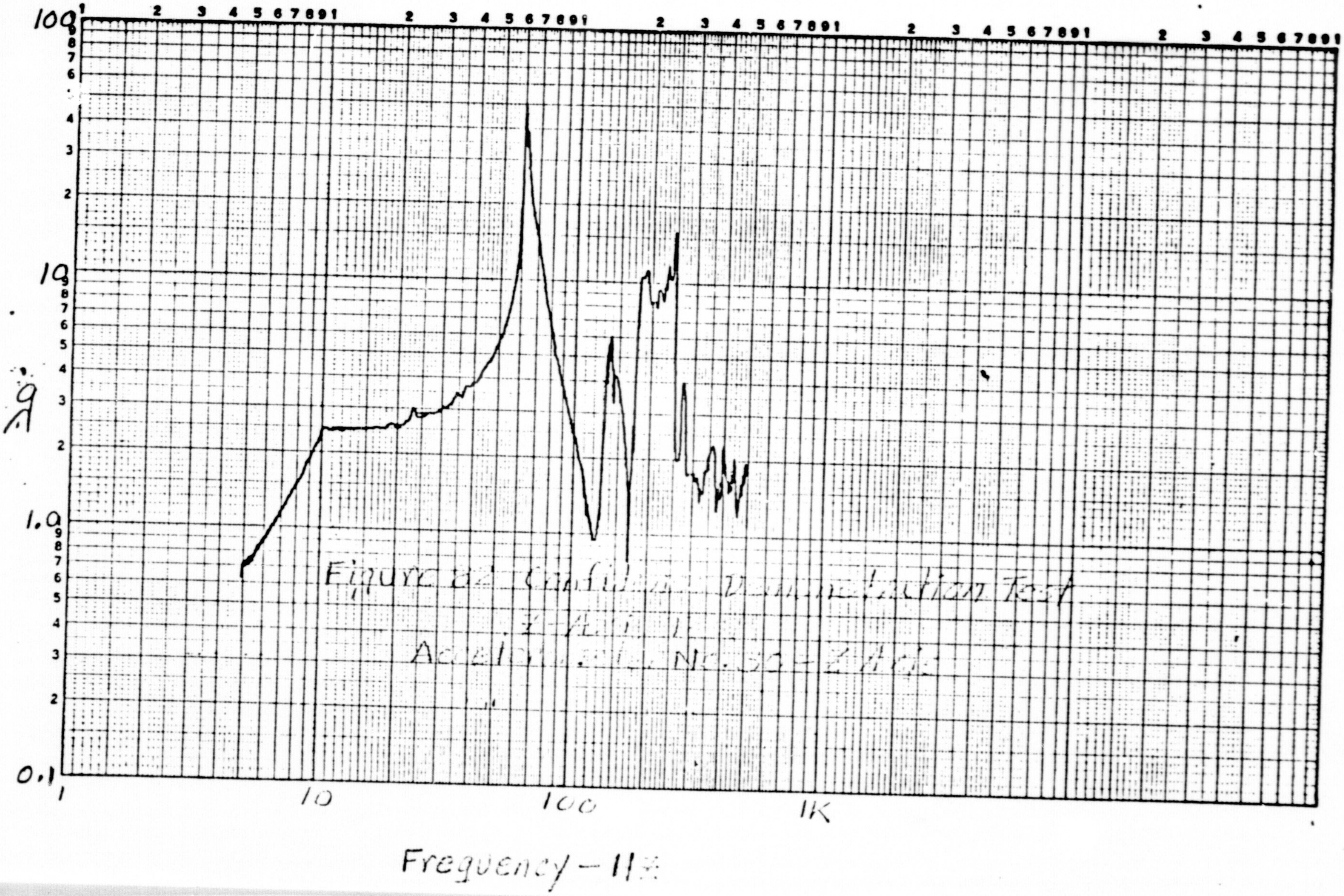

K·E LOGARITHMIC 3 X 5 CYCLES
46 7522 MADE IN U.S.A.
KEUFFEL & ESSER CO.
Figure 79 Confidence Demonstration Test
Z-Axis Test
Accelerometer No. 23 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - Hz


K·E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO.
46 7522 MADE IN U.S.A.
Figure 80 Confidence Demonstration Test
Z-Axis Test
Accelerometer No.28 - Z Axis
g
100
10
1.0
0.1
1
10
100
1K
Frequency -- HZ

K•E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7522 MADE IN U.S.A.

Figure 81 Confidence Demonstration Test
Z-Axis Test
Accelerometer No. 29 - Y Axis




100
10
1.0
0.1
g
1
10
100
1K
Frequency - Hz
Figure
Test
No.

b.

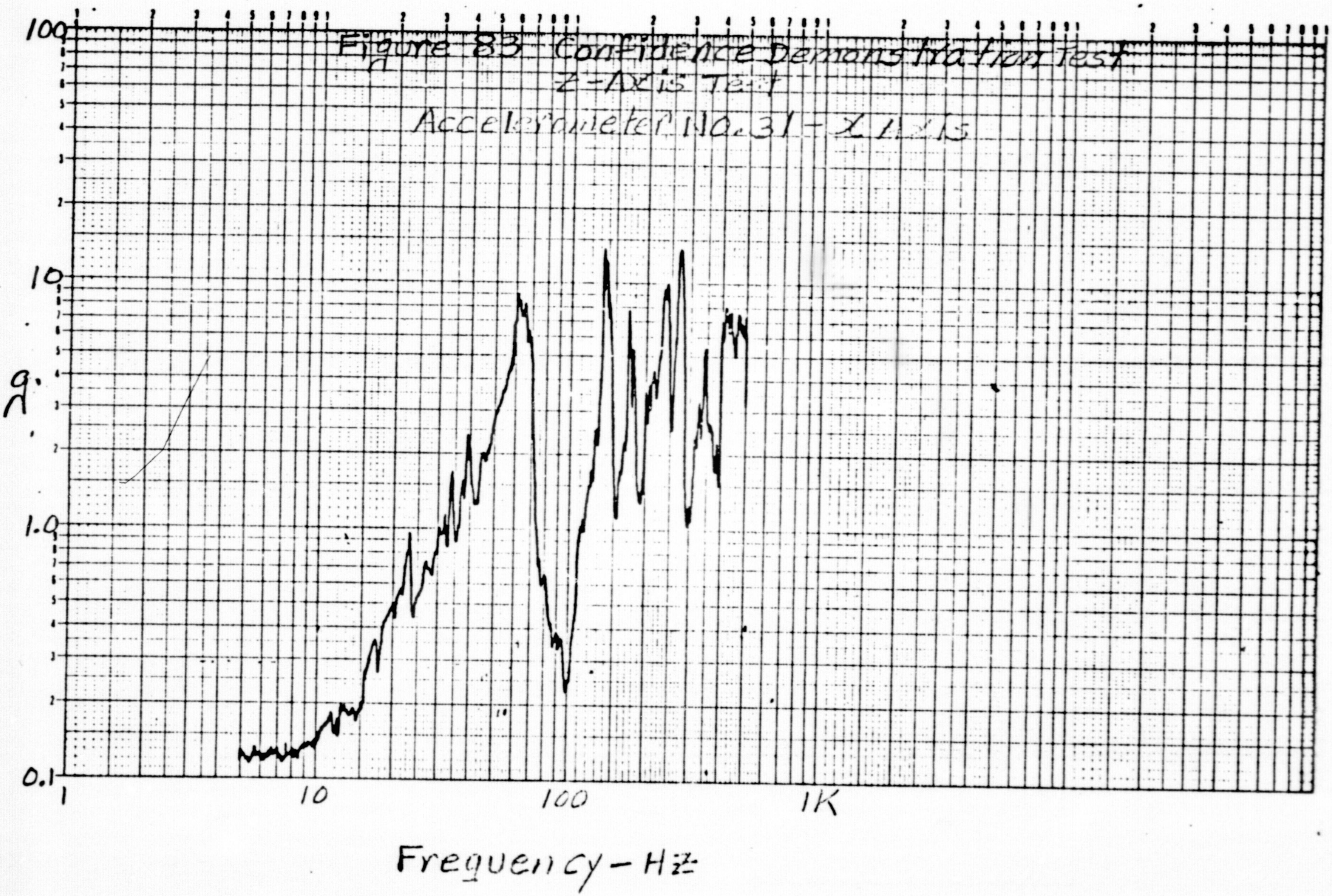


Figure 83 Confidence Demonstration Test
Z-Axis Test
Accelerometer No. 31 - Z Axis

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LOGARITHMIC 3 CYCLES X 5 CYCLES AL-0254-GT

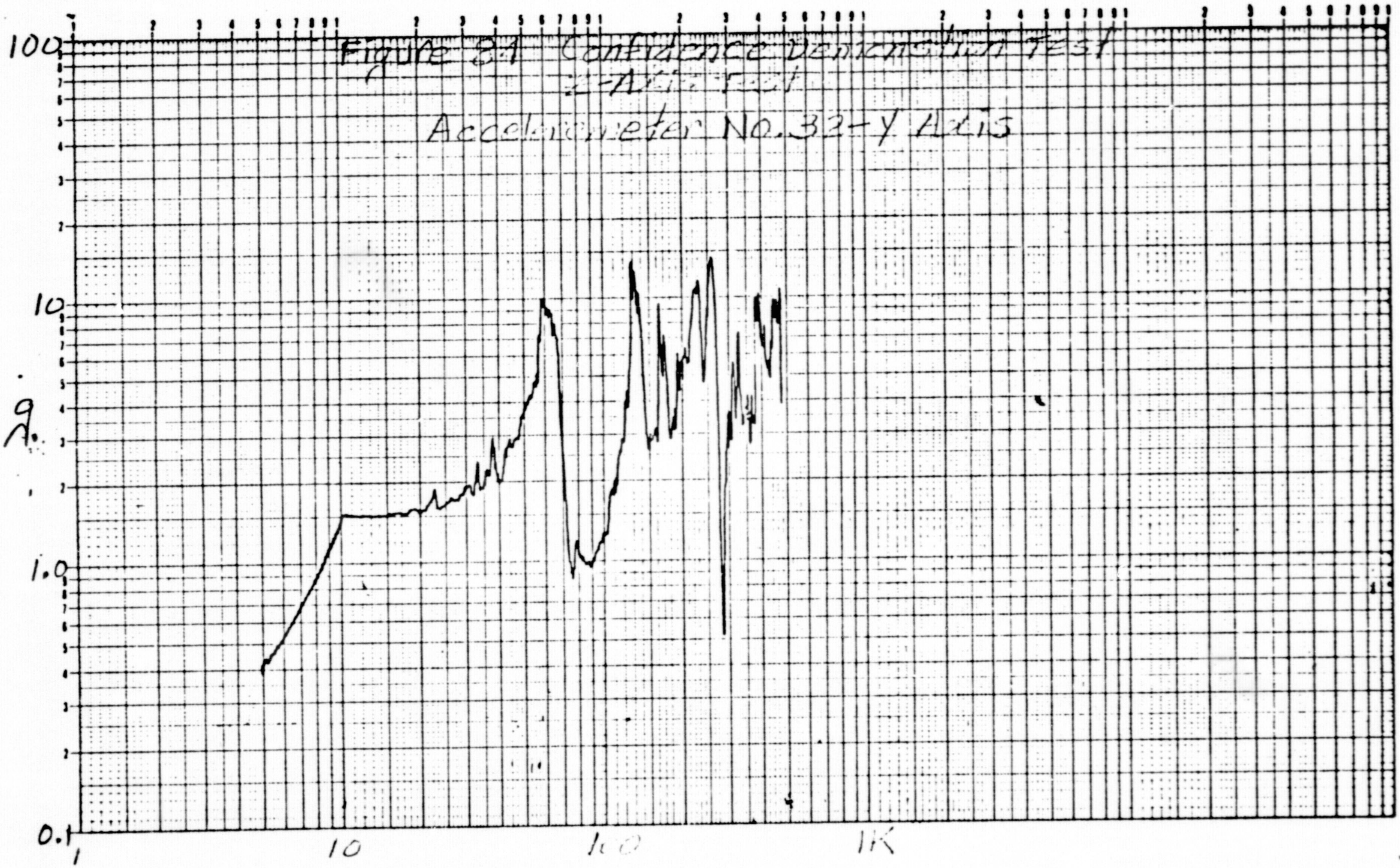


Figure 81 Confidence Demonstration Test
2-Axis Test
Accelerometer No. 32-Y Axis

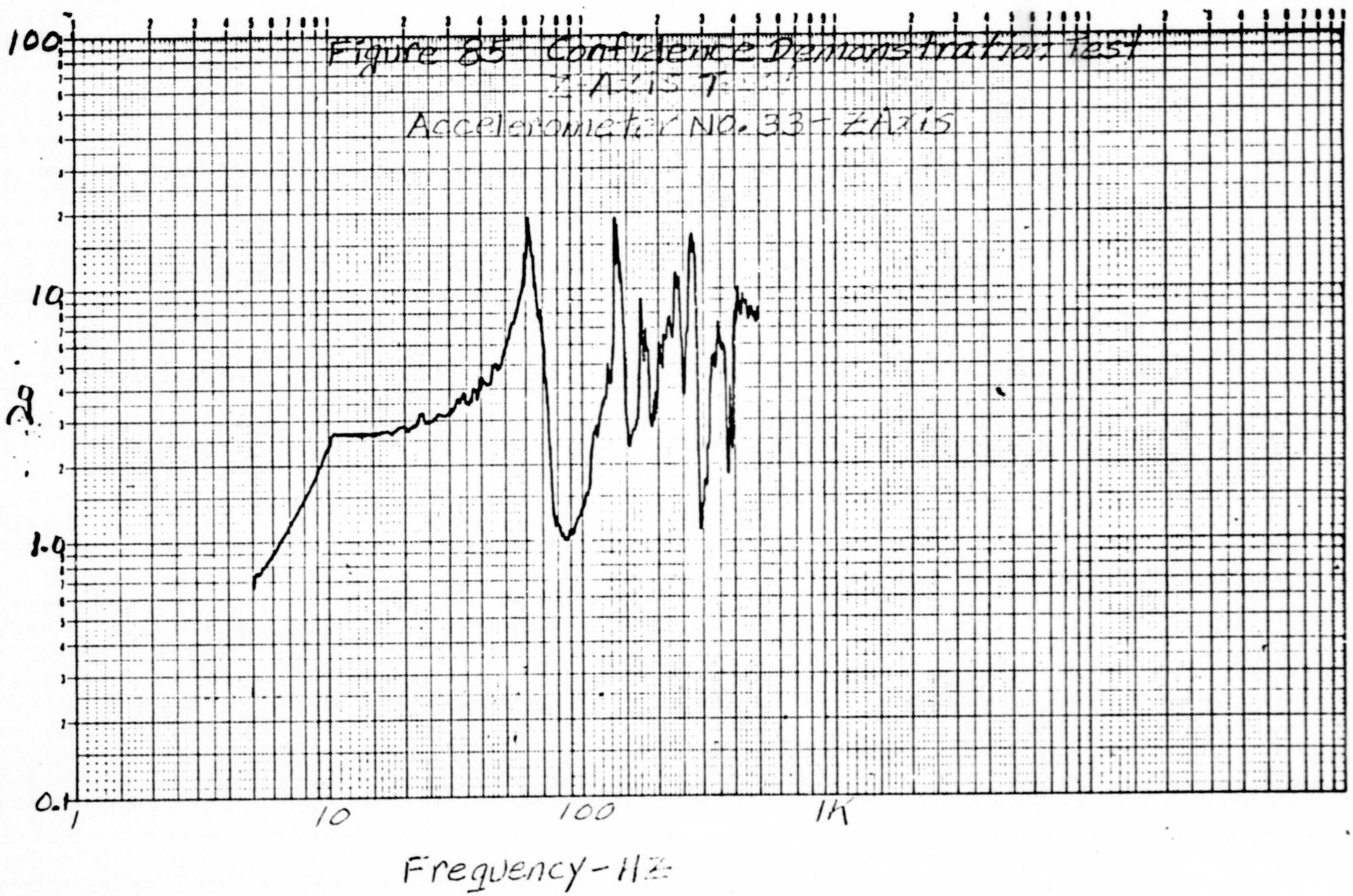
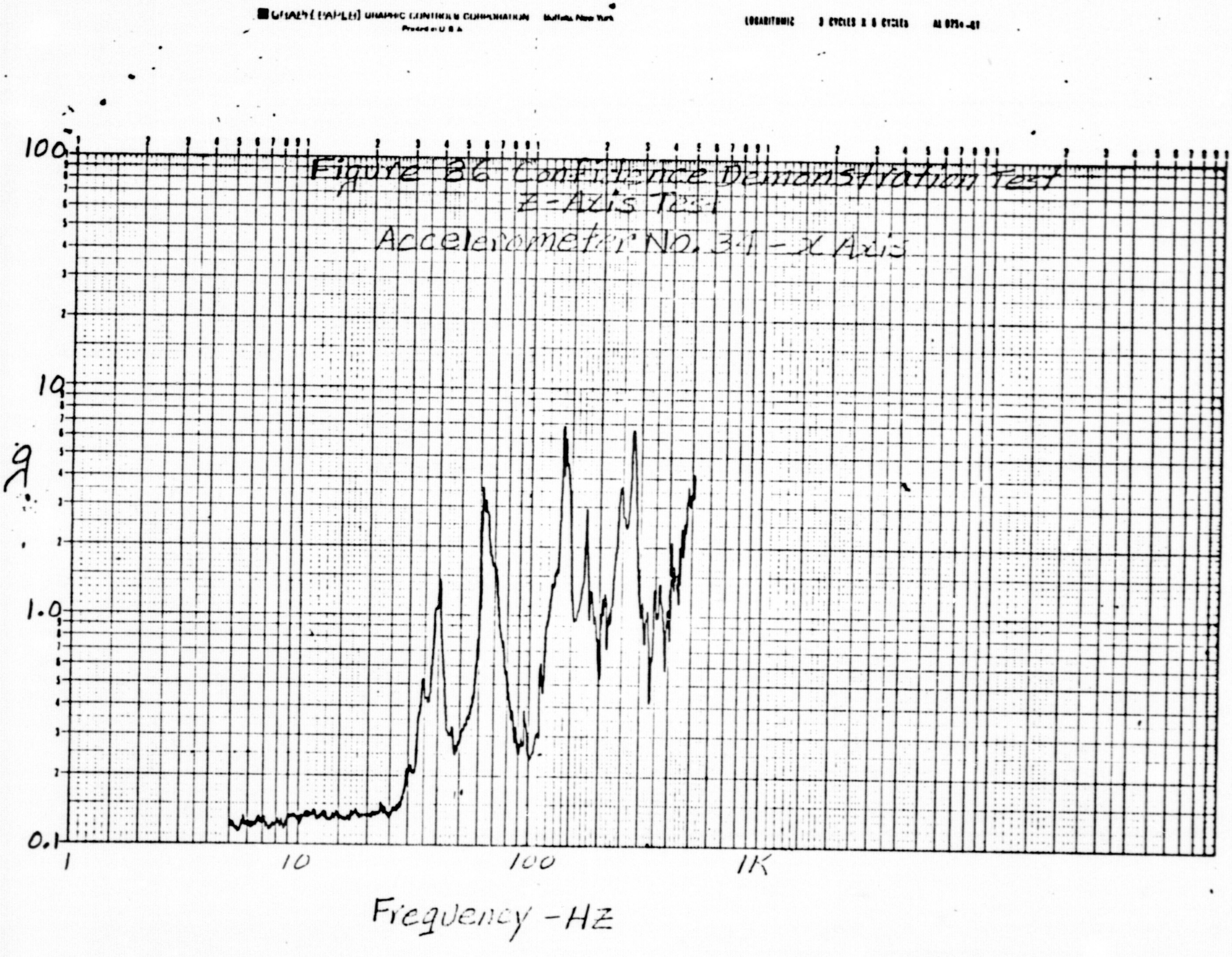


Figure 85 Confidence Demonstration Test
Z-AXIS T
Accelerometer NO. 33 - Z AXIS
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ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LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure 36 Confidence Demonstration Test
Z-Axis Test
Accelerometer No. 31 - X Axis
g
100
10
1.0
0.1
1
10
100
1K
Frequency -HZ

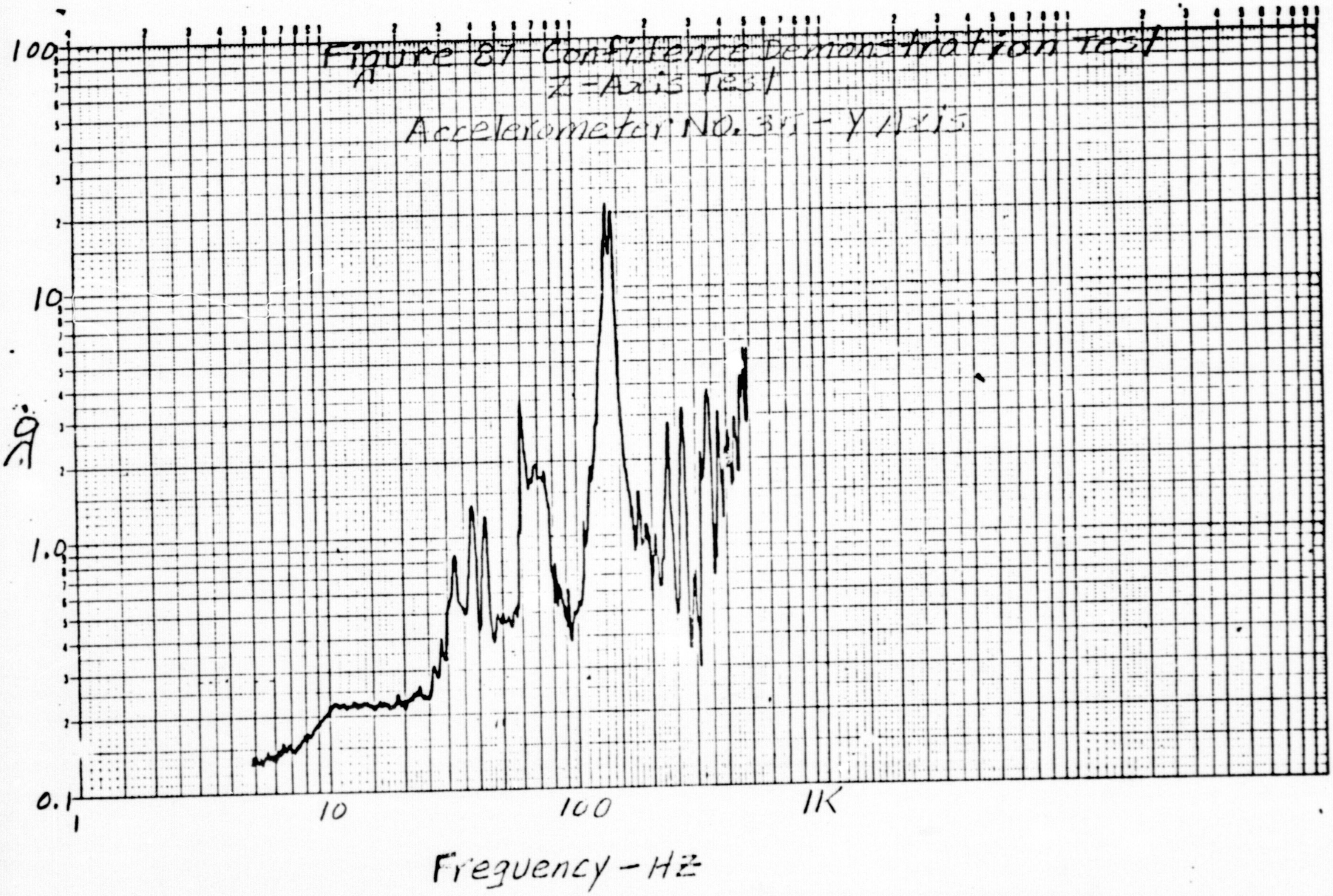
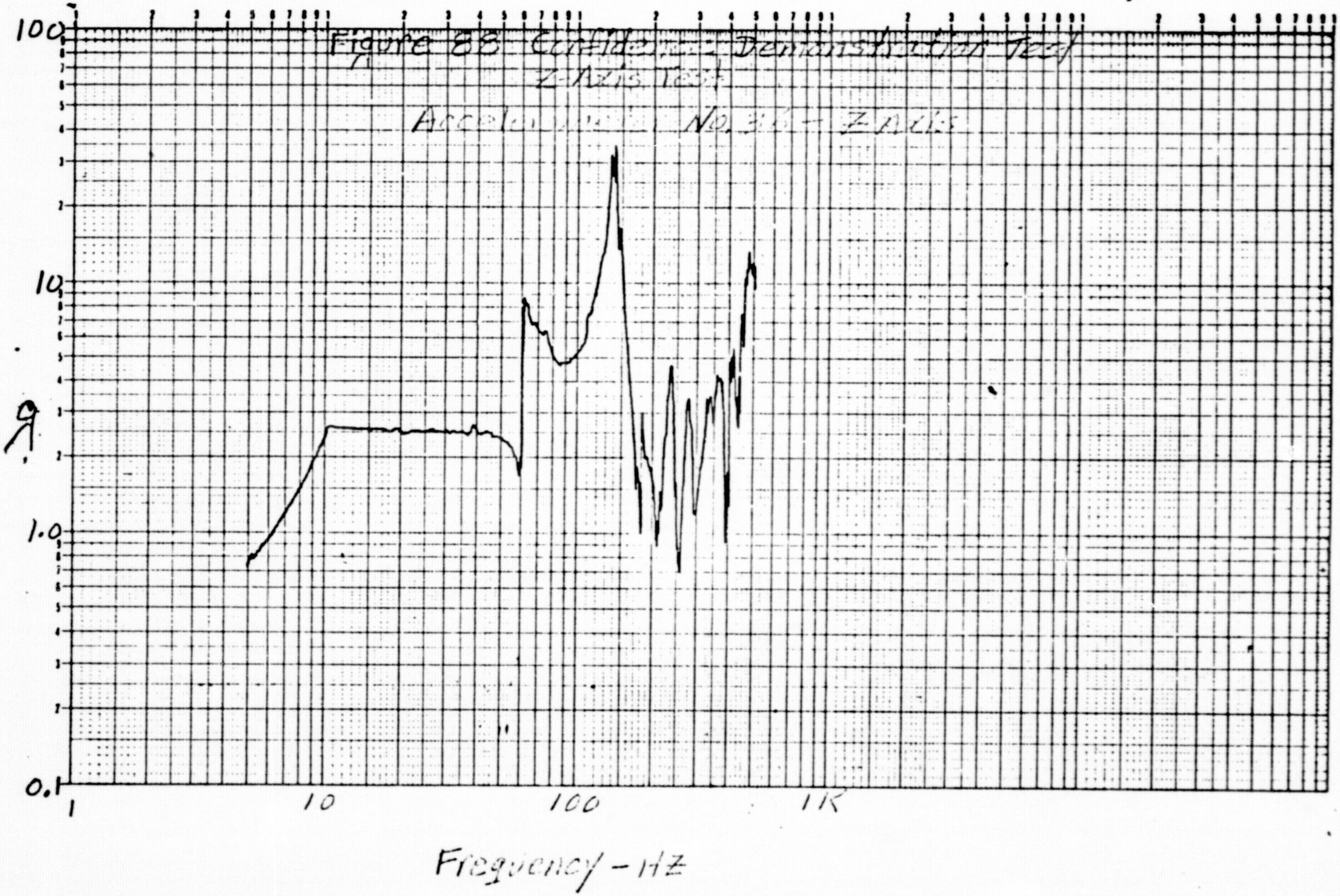
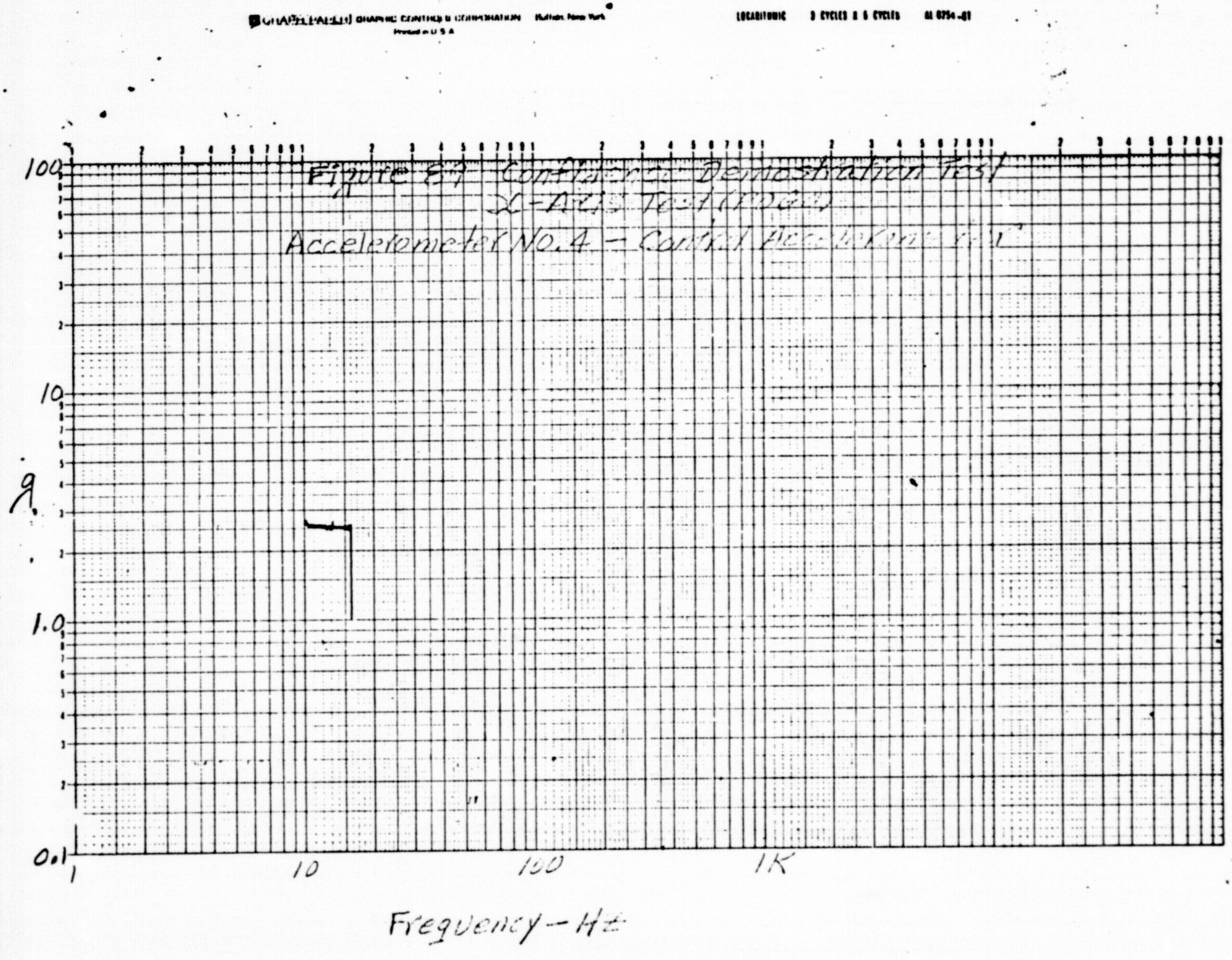


Figure 81 Confidence Demonstration Test
Z-Axis Test
Accelerometer NO. 31 - Y Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ


Z-Axis Test
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ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LOGARITHMIC 3 CYCLES X 5 CYCLES
Figure E7 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 4 – Control
100
10
g
1.0
0.1
1
10
100
1K
Frequency – Hz

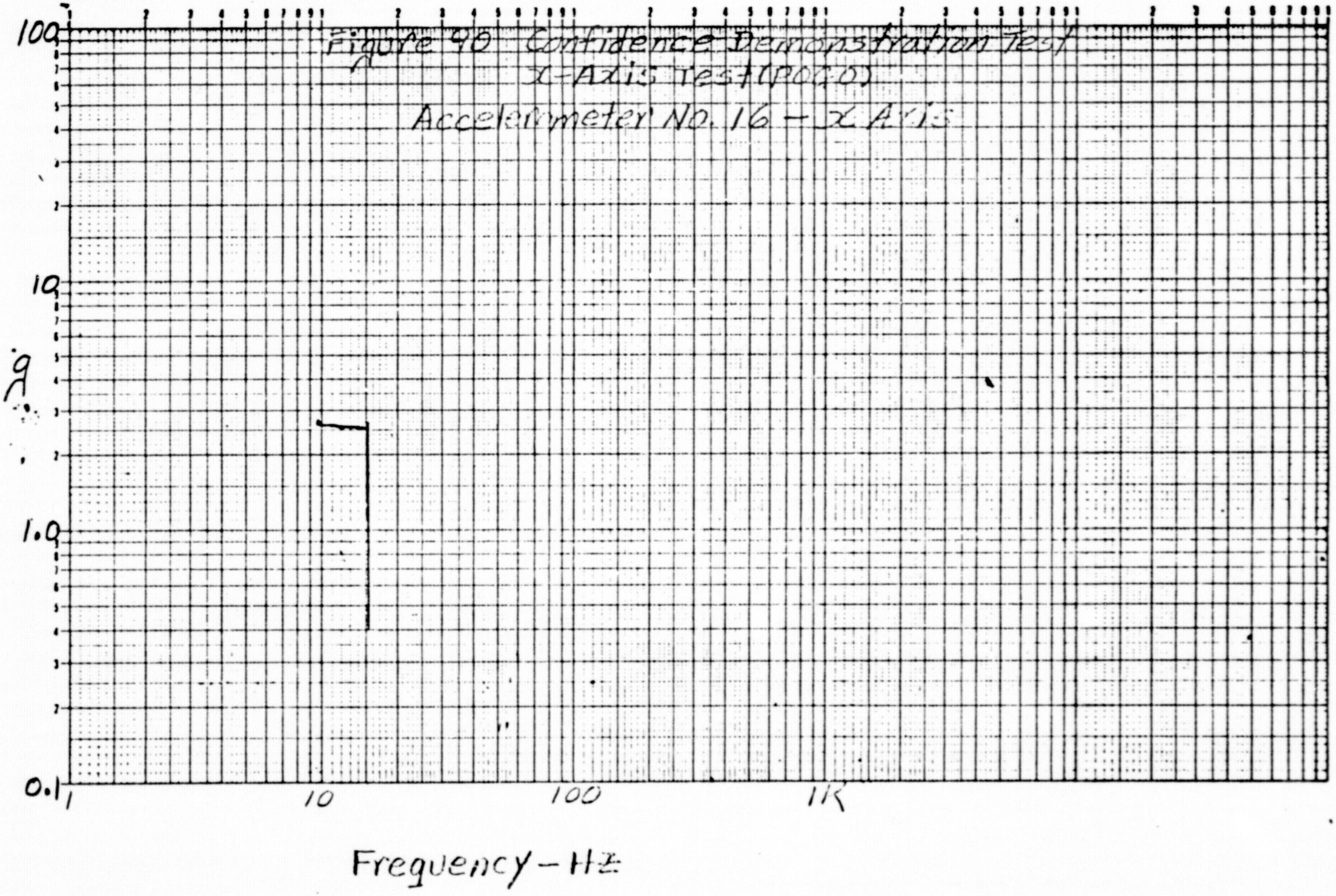


Figure 9D Confidence Demonstration Test
X-Axis Test (POC-D)
Accelerometer No. 16 - X Axis

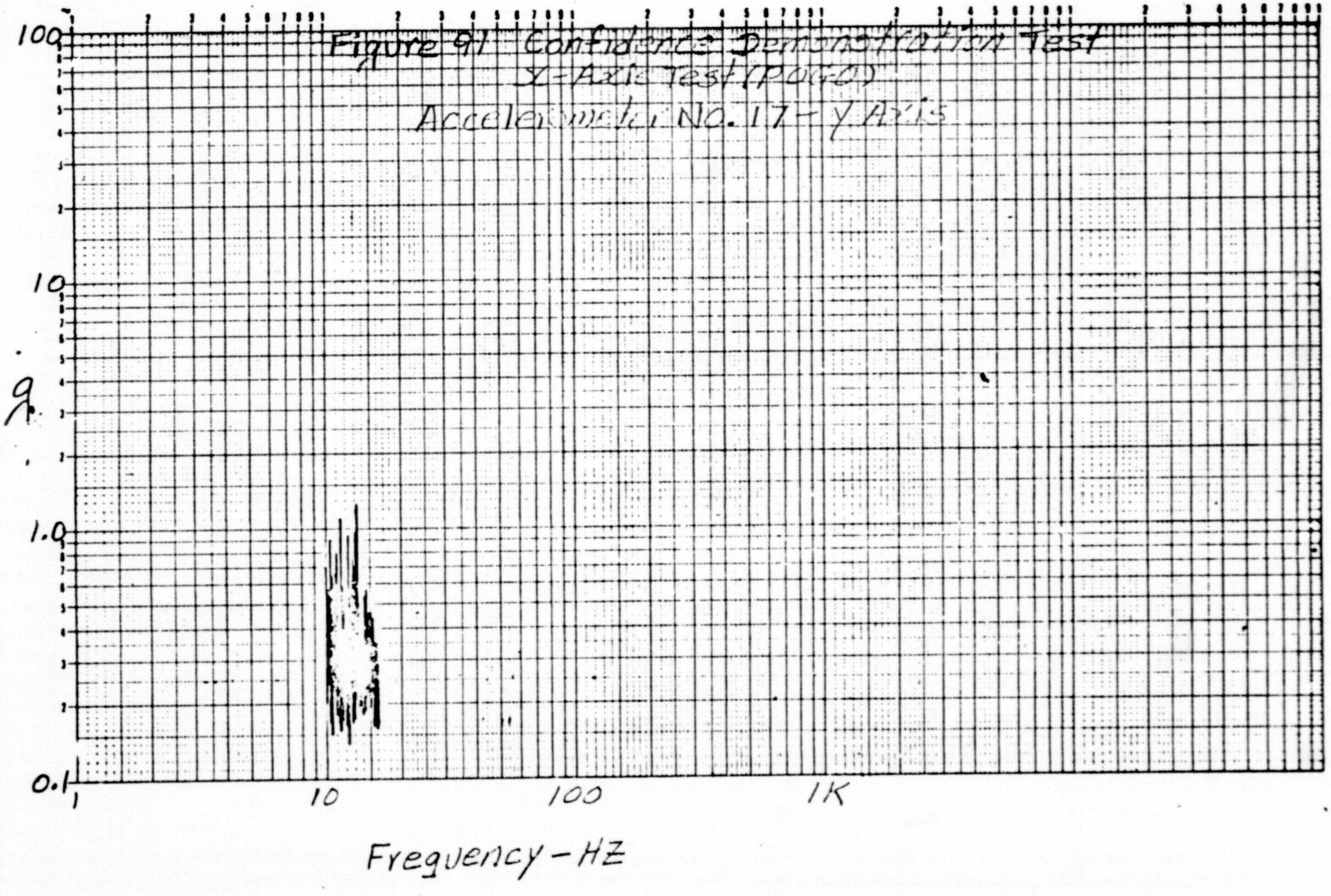
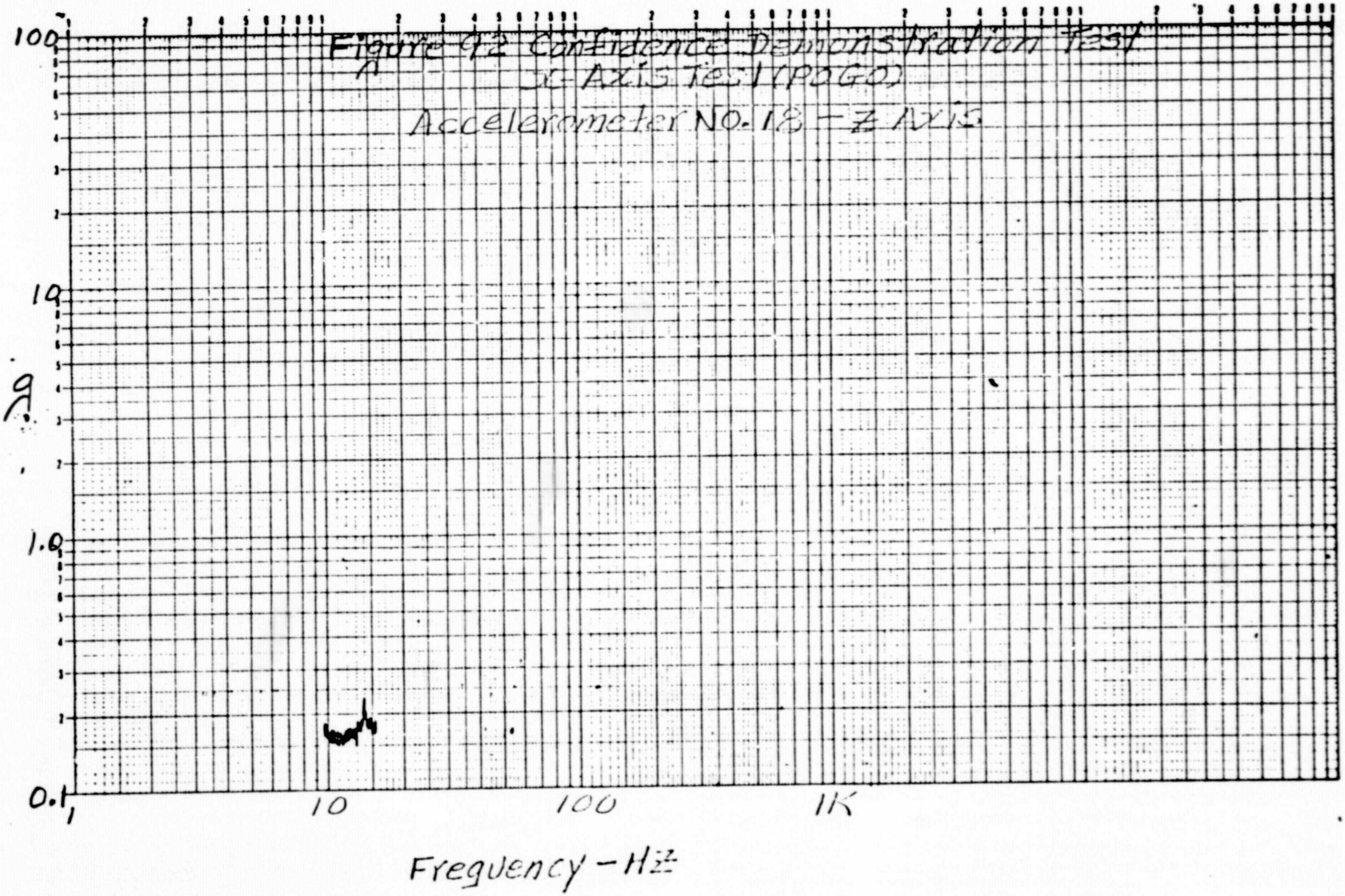


Figure 91 Confidence Demonstration Test
X-Axis Test (POGO)
Accelerometer No. 17 - Y Axis

Figure 92A Confidence Demonstration Test
X-Axis Test (POGO)
Accelerometer No. 18 - Z Axis



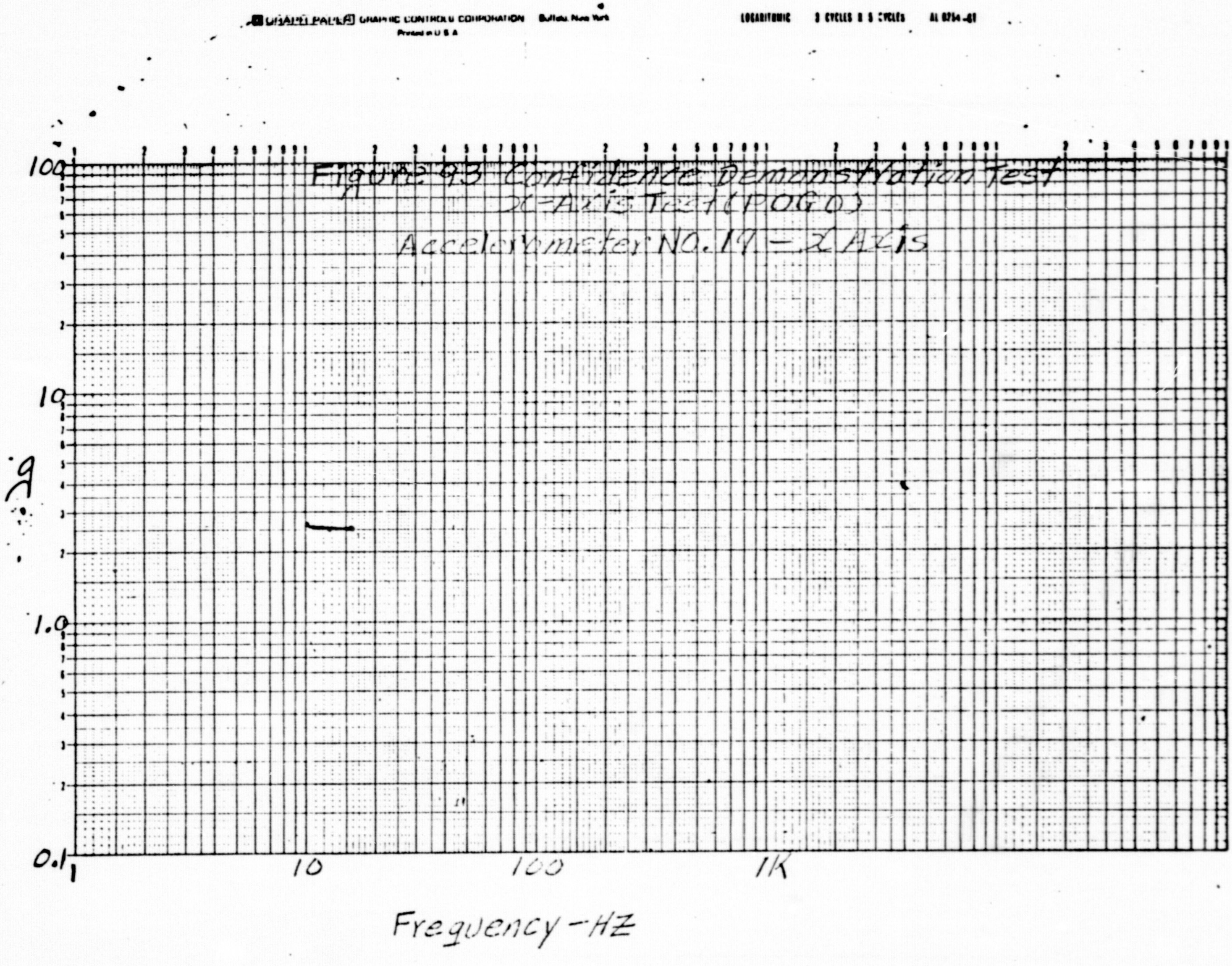

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Figure 93 Confidence Demonstration Test
X-Axis Test (POGO)
Accelerometer NO. 17 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ

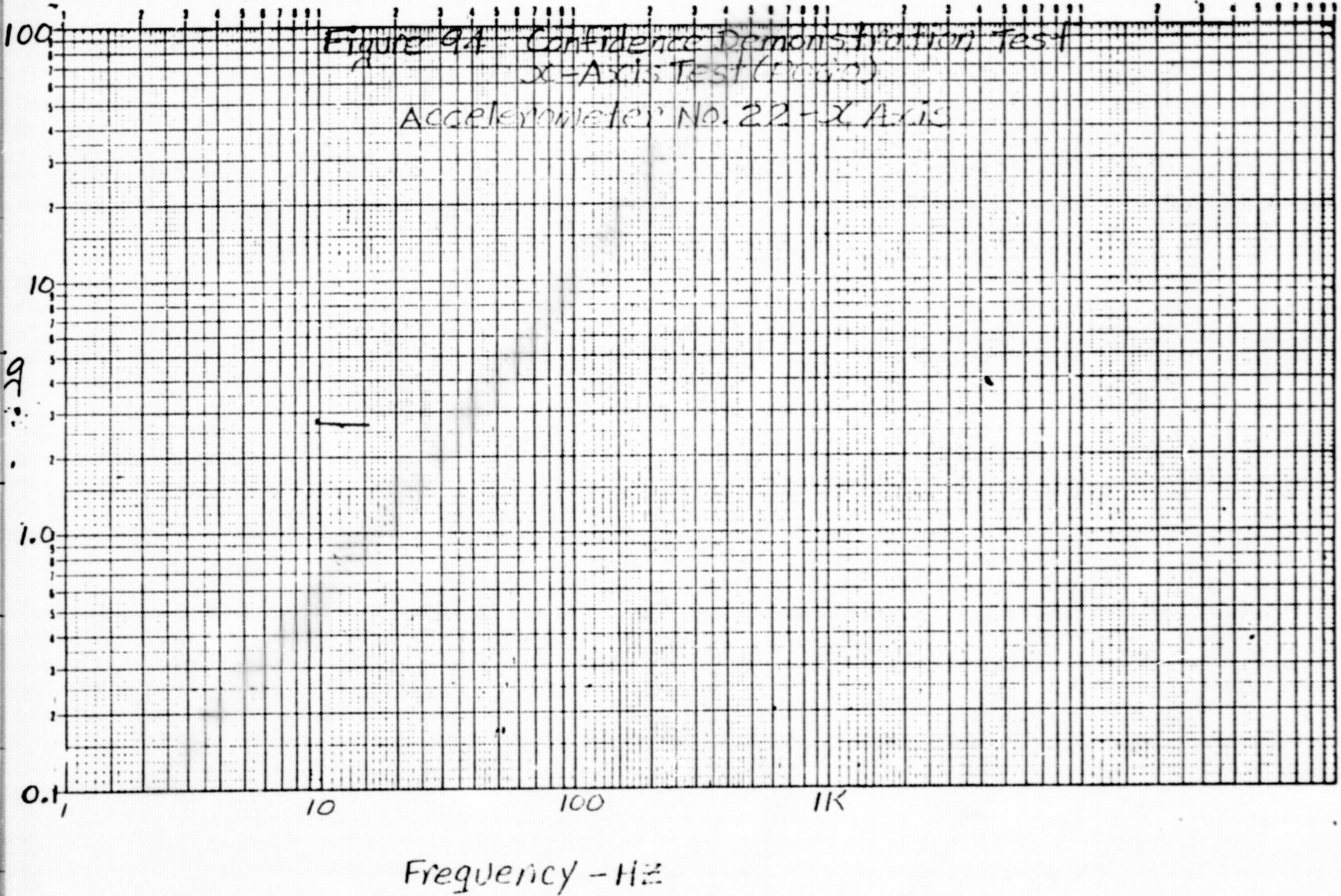
Figure 94 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 22 - X Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

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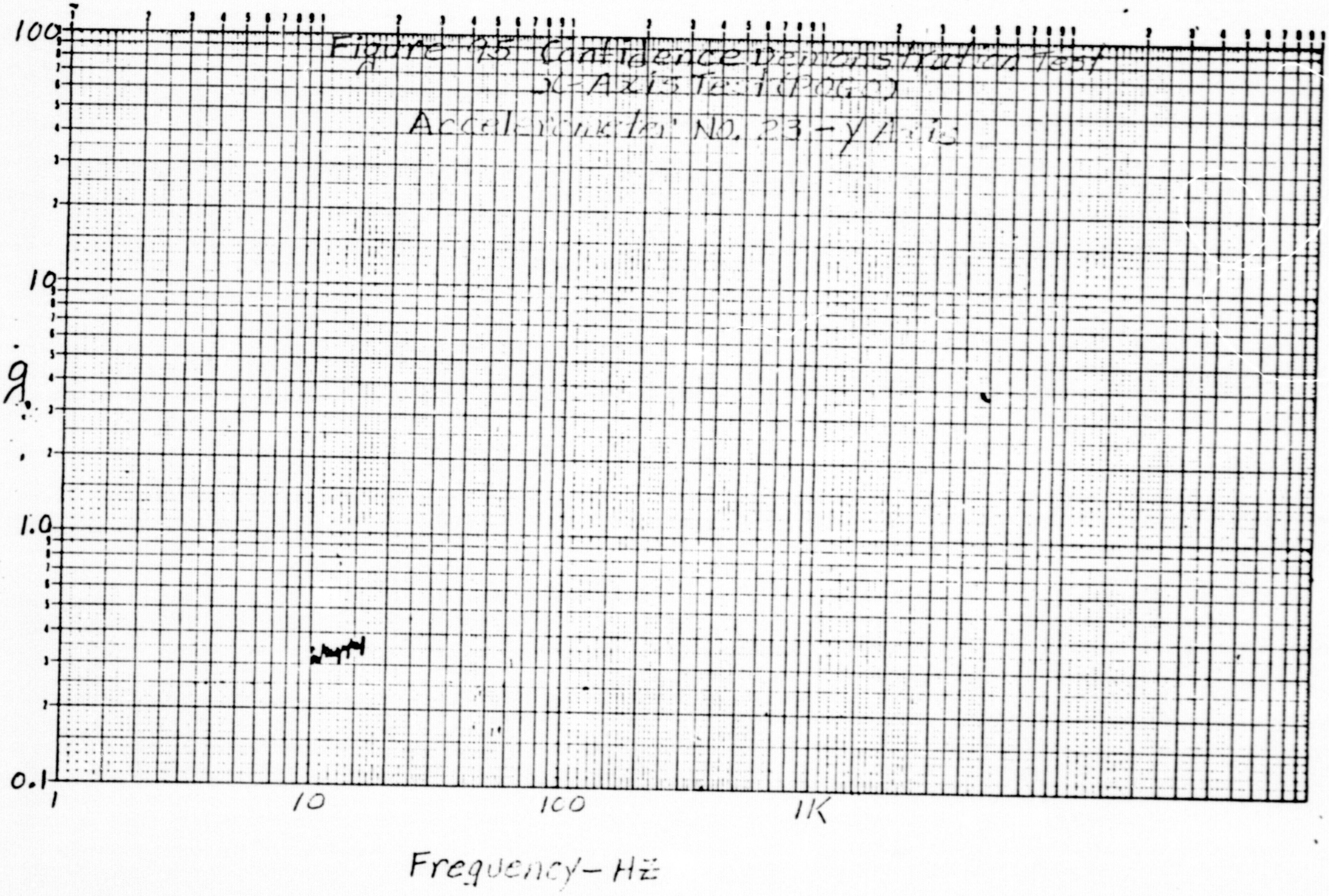
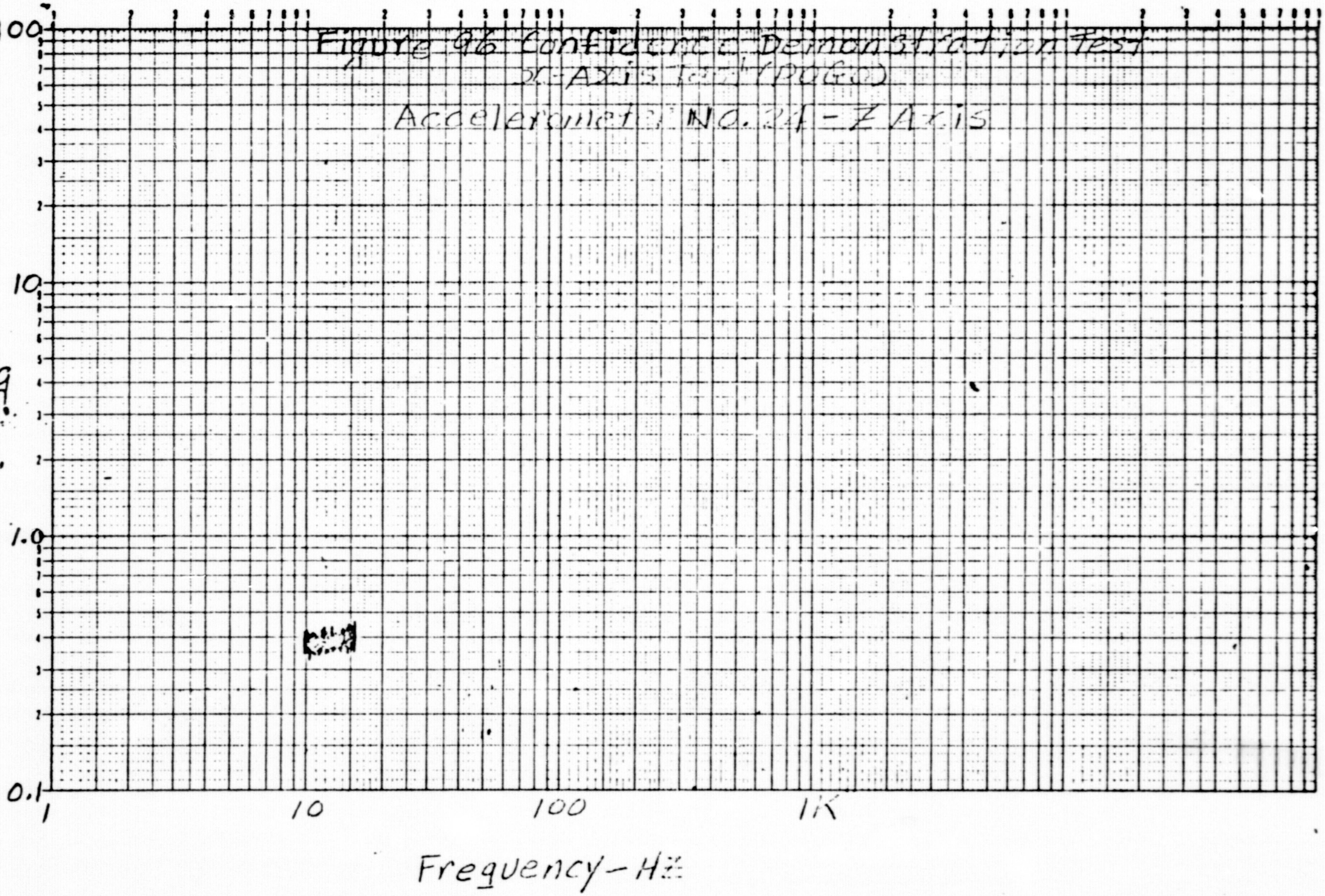


Figure 96 Confidence Demonstration Test
X-Axis Test (POGO)
Accelerometer No. 24 - Z Axis



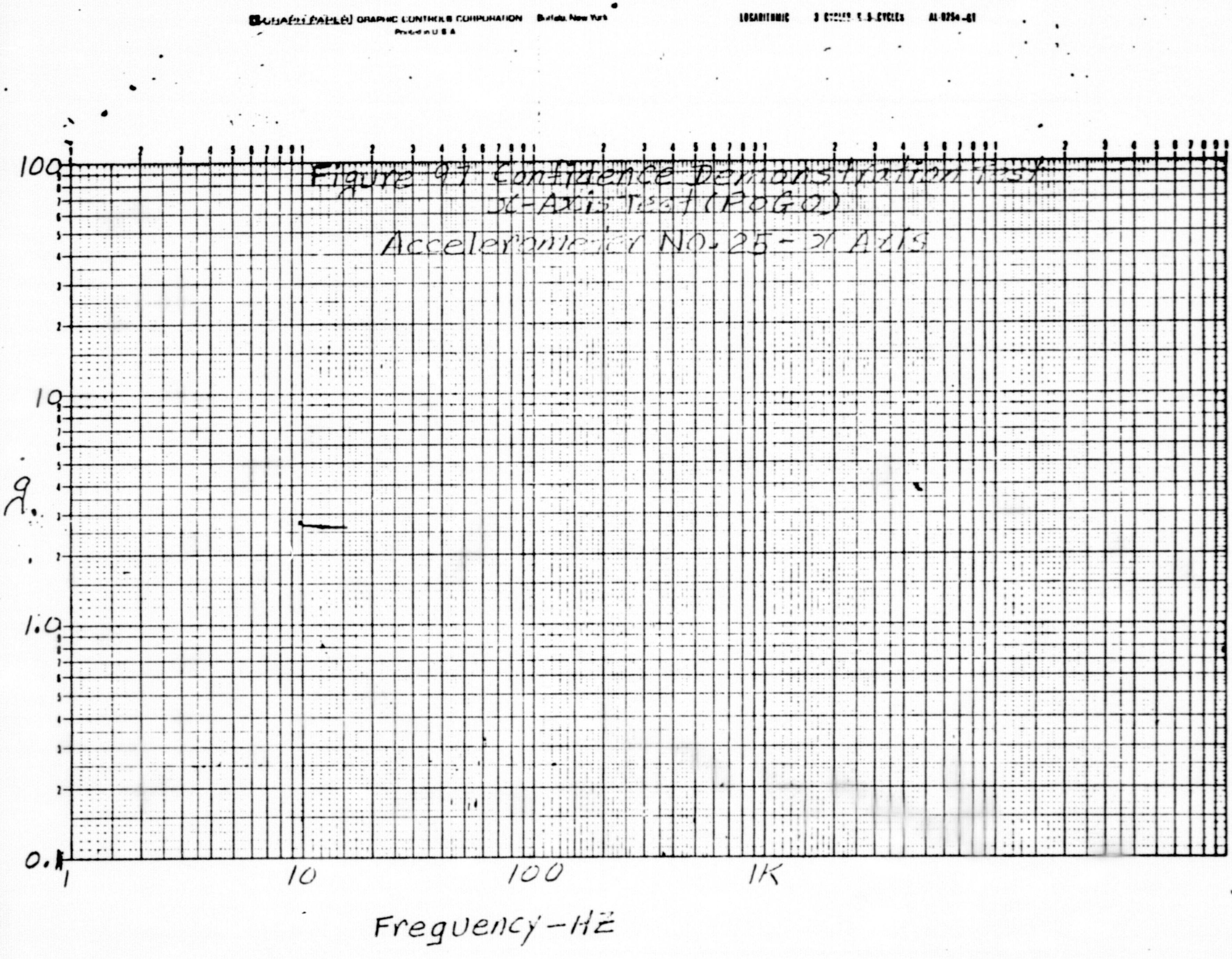


Figure 97 Confidence Demonstration Test
x-Axis Test (POGO)
Accelerometer NO. 25 - x Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency - HZ

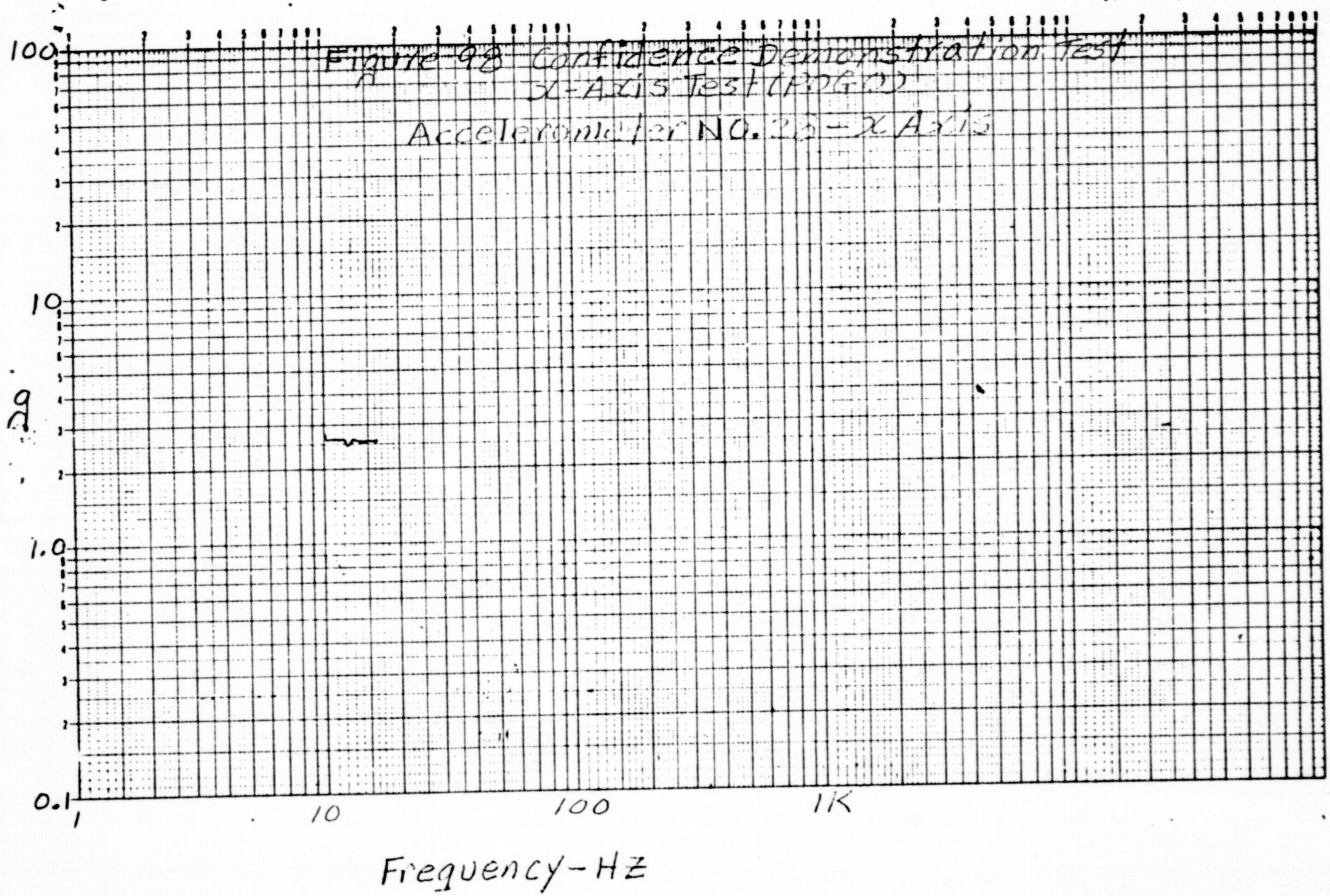


Figure 98 Confidence Demonstration Test
X-Axis Test (PDG?)
Accelerometer NO. 25 - X Axis
100
10
1.0
0.1
g
1
10
100
1K
Frequency-HZ

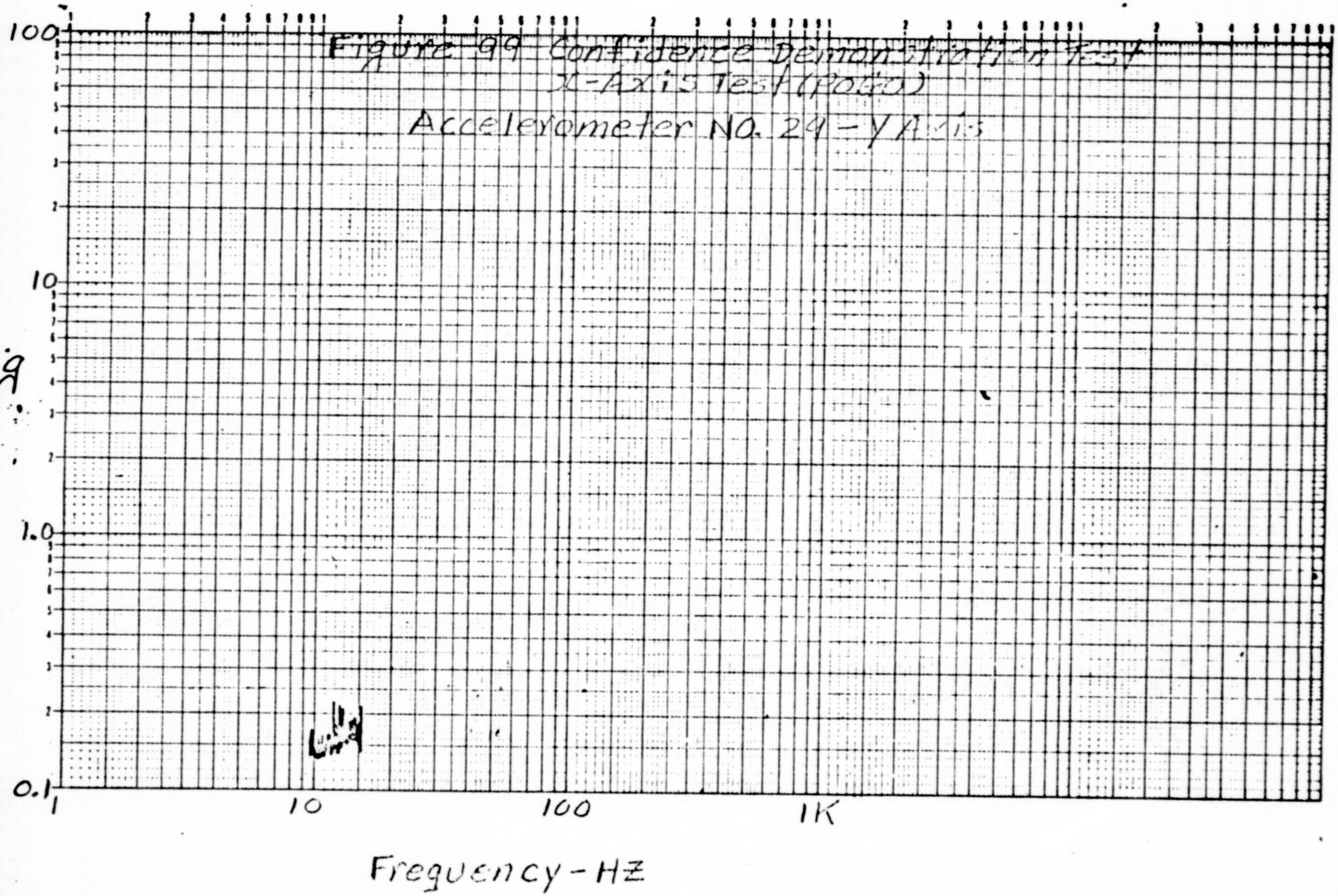
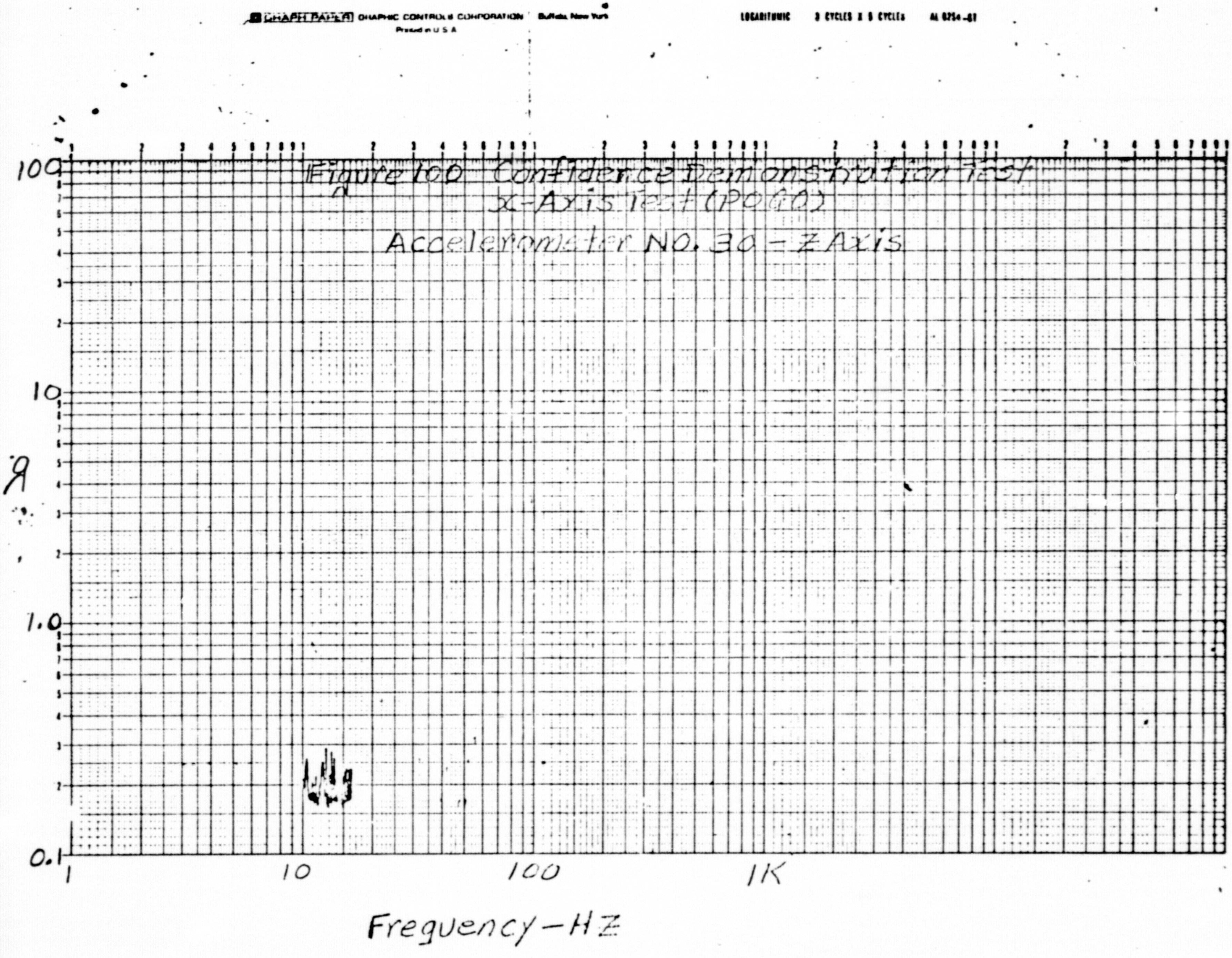


Figure 99 Confidence Demonstration Test
X-Axis Test (Pogo)
Accelerometer NO. 24 - Y Axis

Figure 100 Confidence Demonstration Test
X-Axis Test (POGO)
Accelerometer NO. 30 - Z Axis



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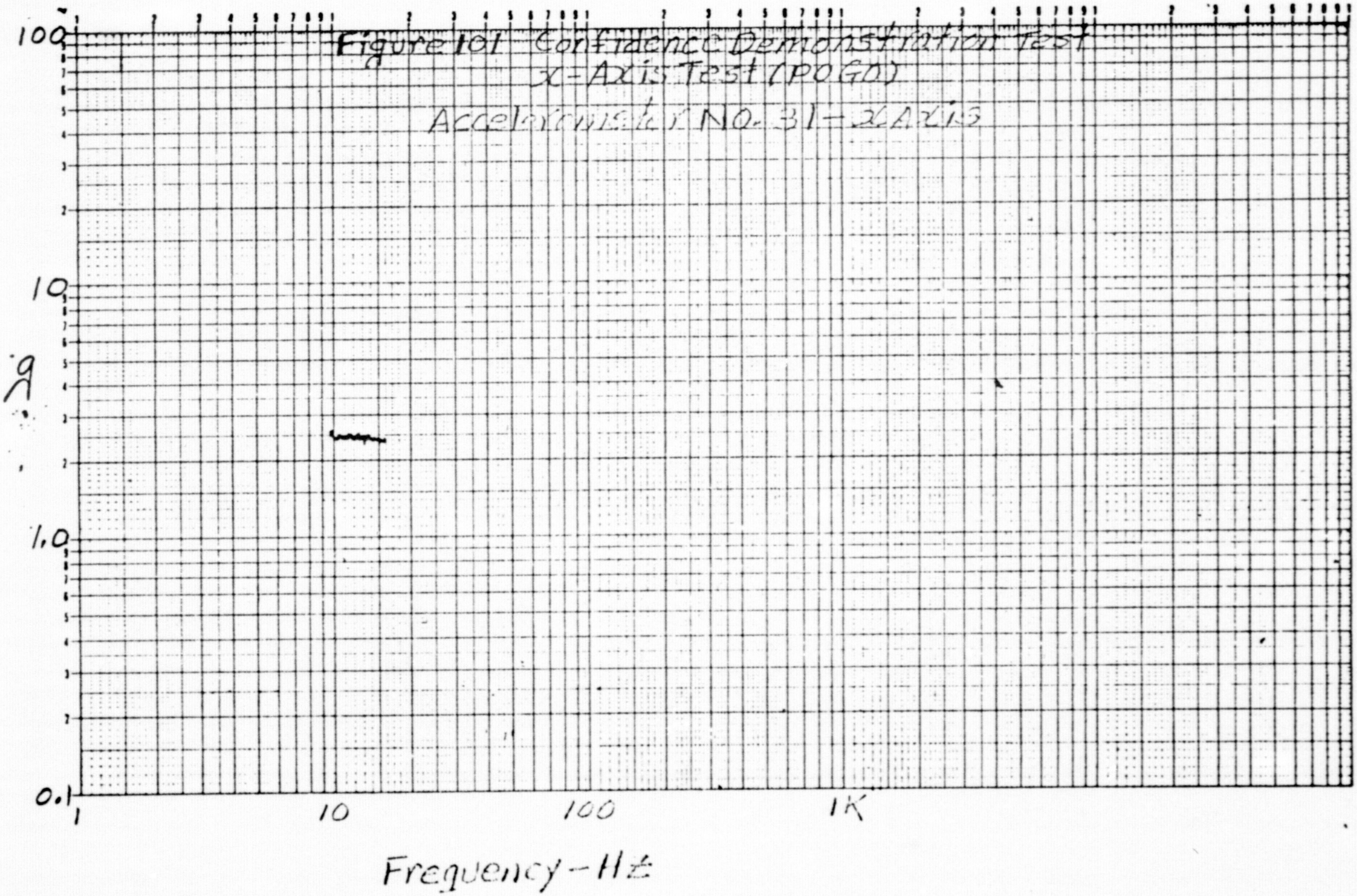
1



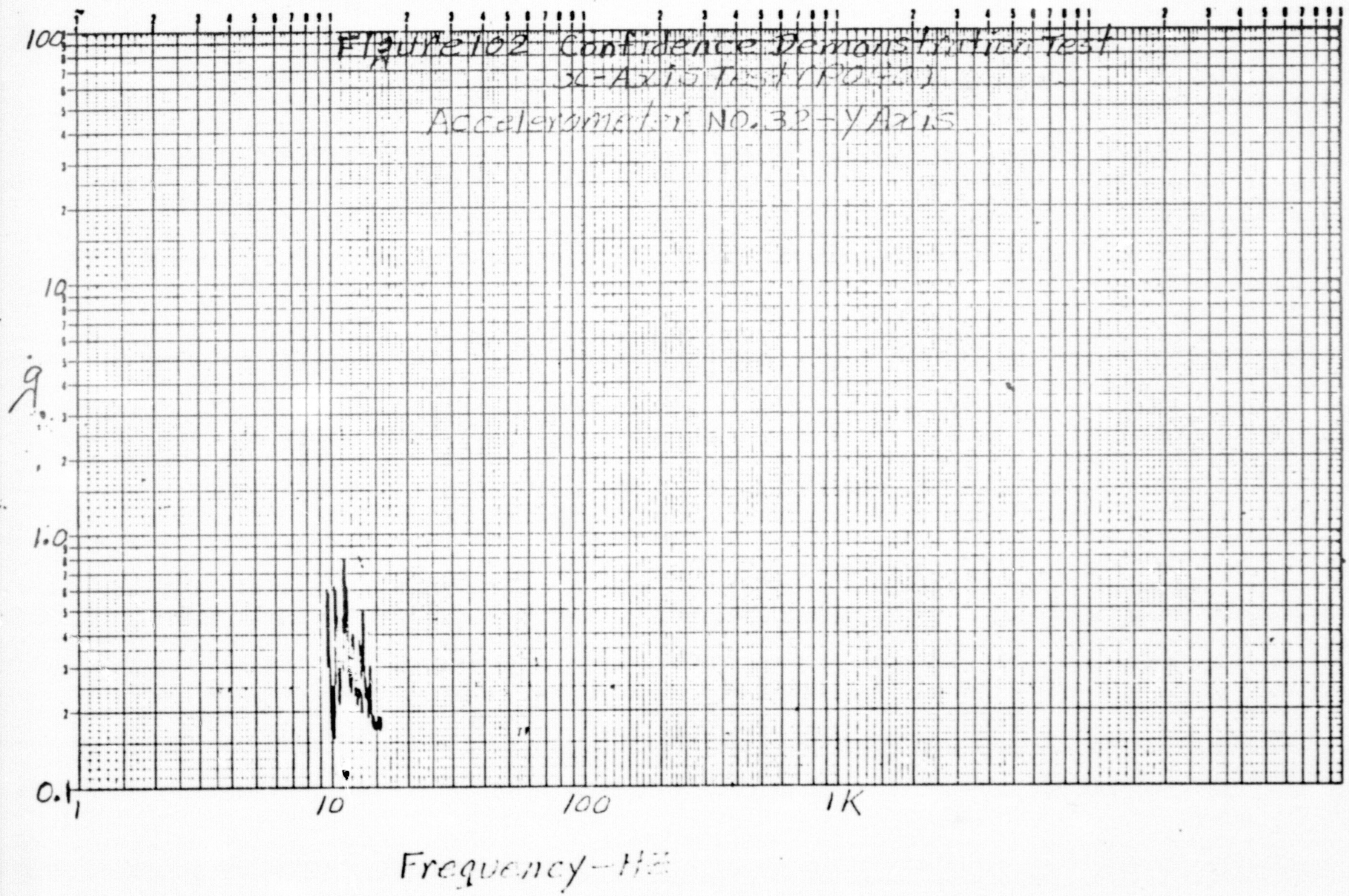


Figure 102 Confidence Demonstration Test
Accelerometer NO. 32 - Y Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency—Hz

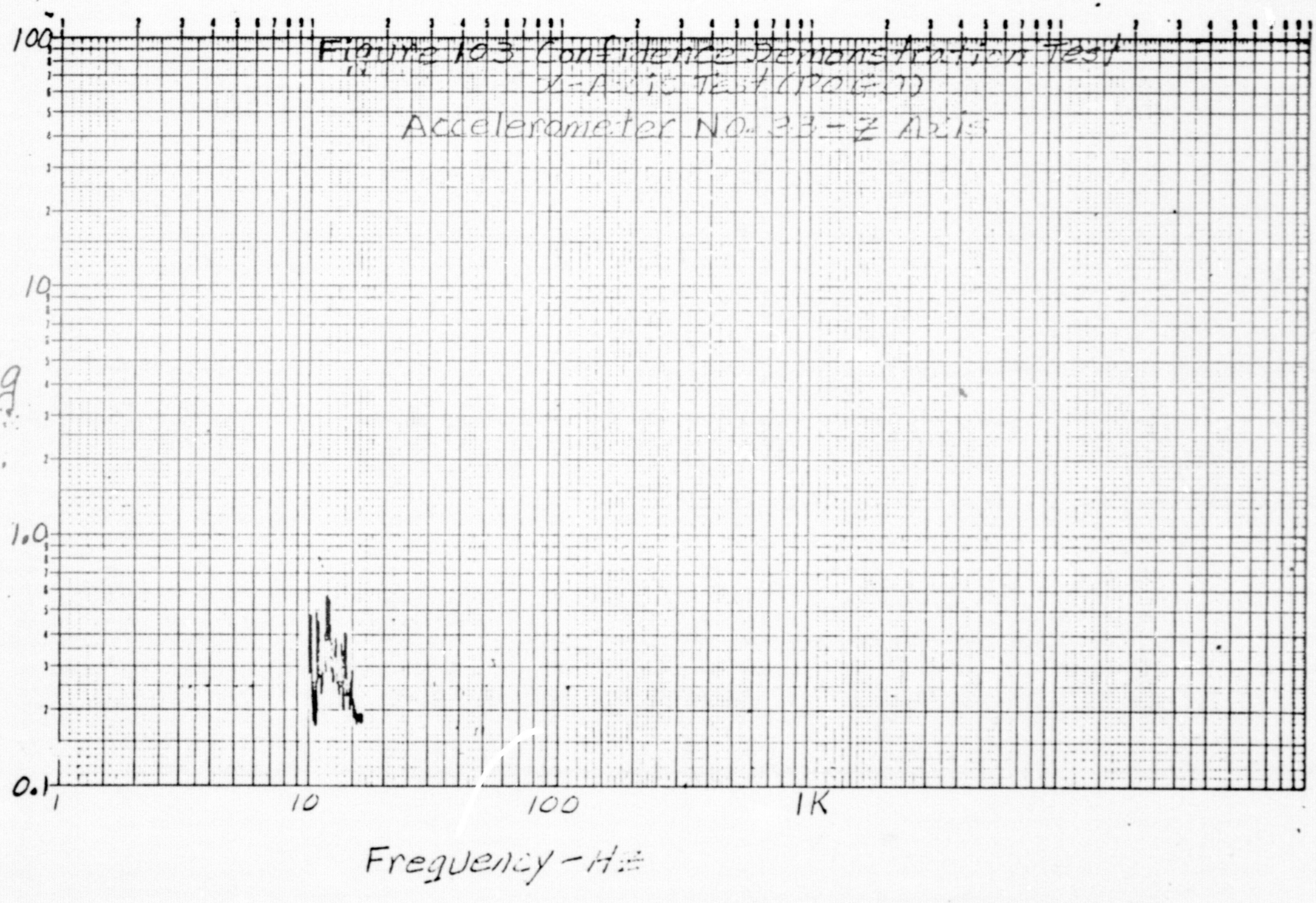


Figure 103 Confidence Demonstration Test
X-Axis Test
Accelerometer NO. 33 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

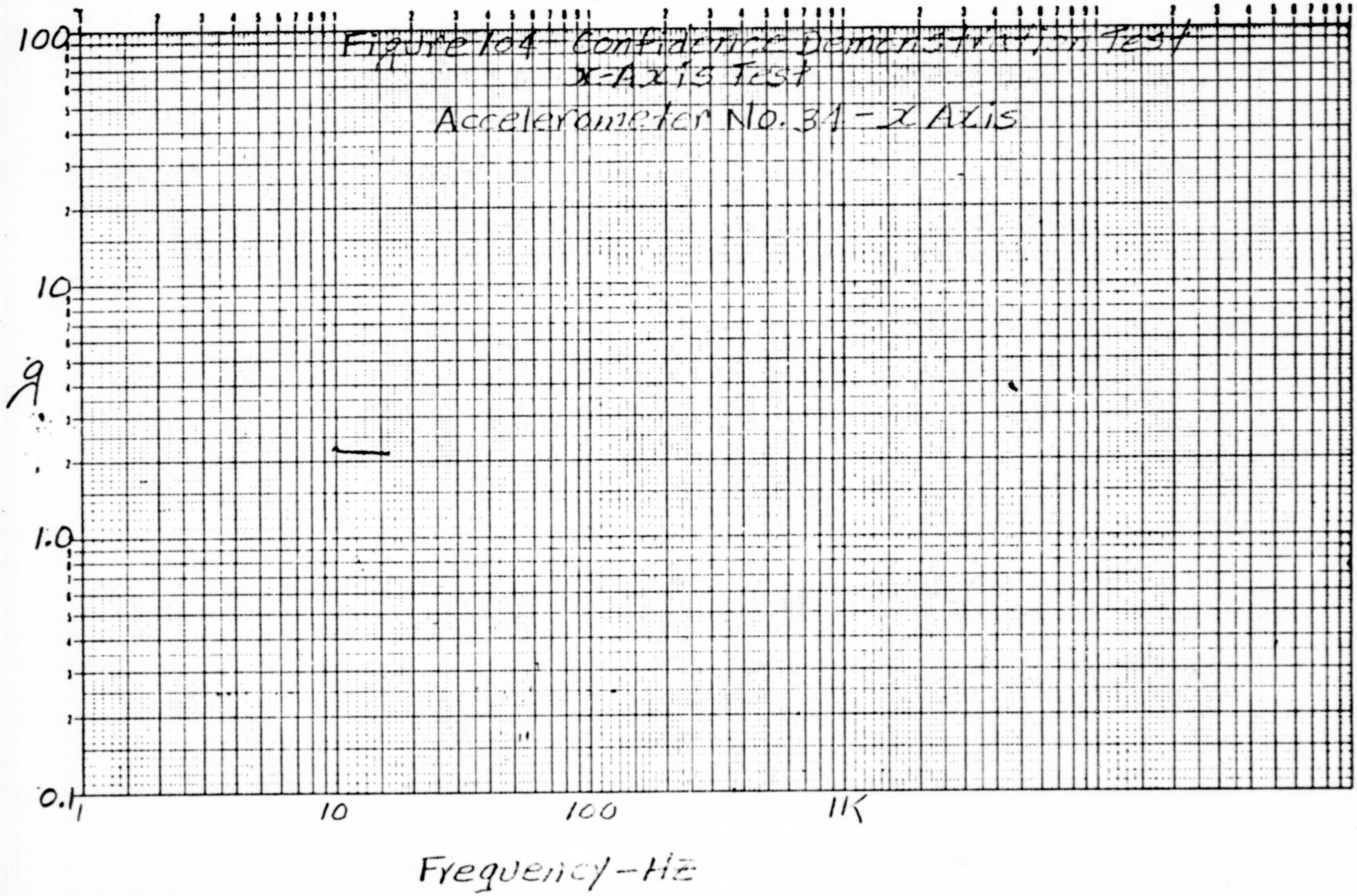


Figure 104 Confidence Demonstration Test
X-Axis Test
Accelerometer No. 34 - X Axis
100
10
g
1.0
0.1
1
10
100
1K
Frequency - Hz

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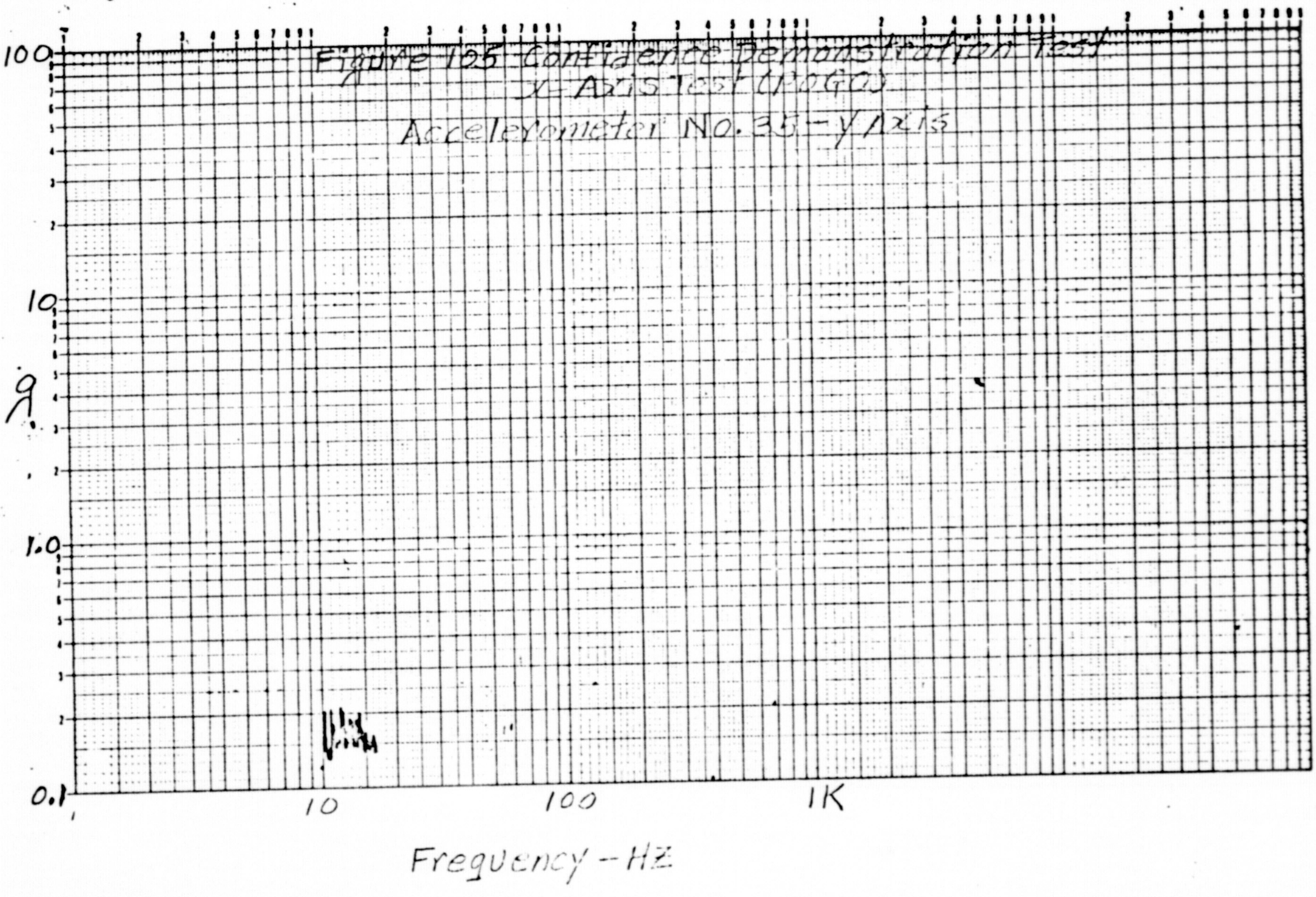
LOGARITHMIC 3 CYCLES X 5 CYCLES AL 0254-01

Figure 105 Confidence Demonstration Test
X-Axis Test (PoGo)
Accelerometer No. 35 - Y Axis



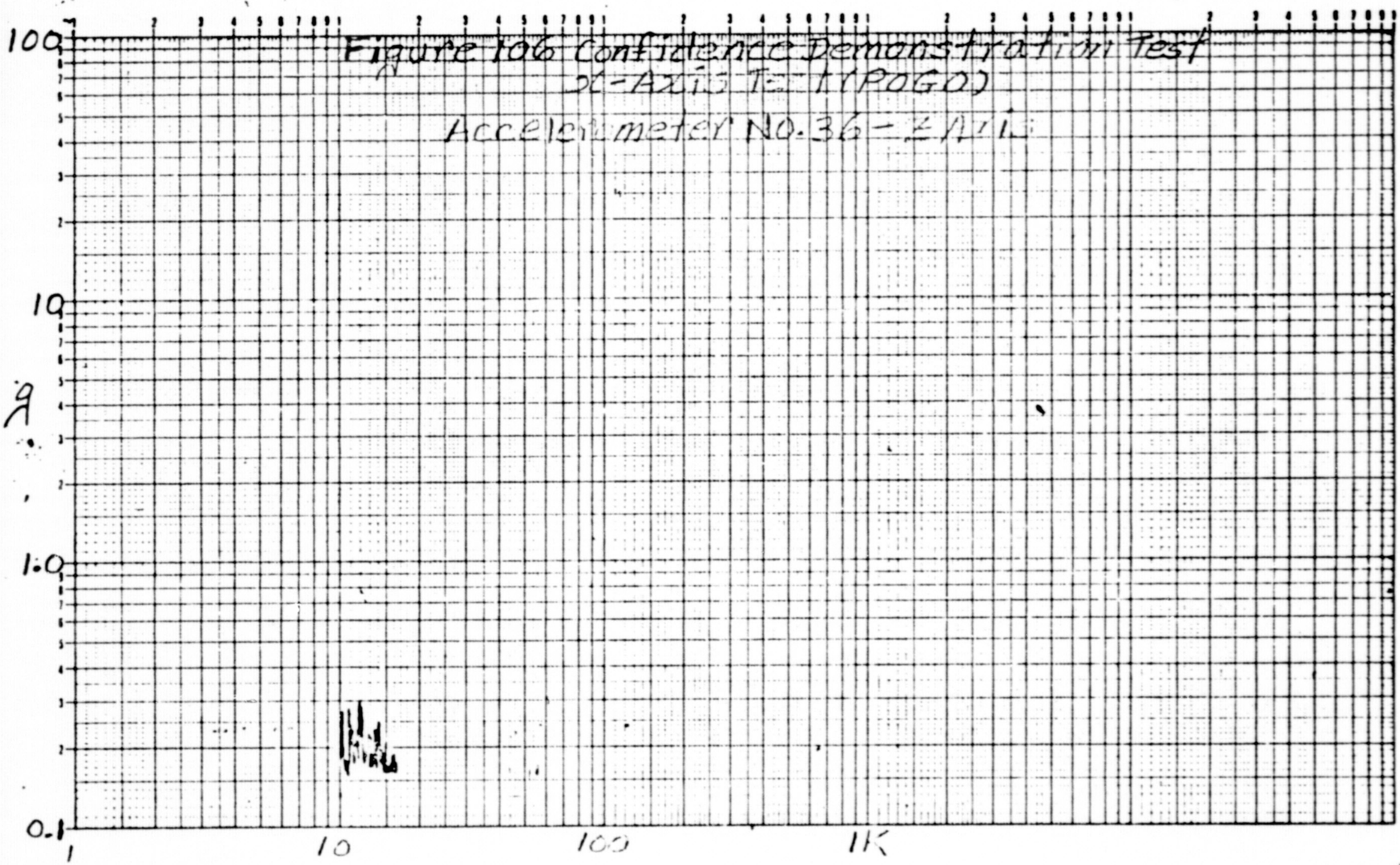


Figure 106 Confidence Demonstration Test
X-Axis Test (POGO)
Accelerometer No. 36 - Z Axis
100
10
g
1.0
0.1
1
10
100
1K